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The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

In-situ Acoustic Received Level Measurements With Glider Based Reactive Behaviour

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***Abstract*—Buoyancy-driven underwater gliders are typically employed to sample the water column environment in the ocean [1]. As one of the efforts of extending the capabilities of traditional underwater gliders, CMRE has been working on the ability of gliders to react to signals of interest. This capability was implemented in a Teledyne Webb Research SLOCUM glider [2], and performed via acoustic signals. During the MED-REP14 sea trial, conducted in June 2014 offshore the west coast of Sardinia (Italy), a hydrophone equipped SLOCUM glider was programmed to react to a signal simulating the line spectrum features of ship radiated noise. Upon the signal of interest being detected, the glider was scheduled to dive to a pre-determined depth and then measure continuously the acoustic received level as a function of depth and range while it was surfacing. At the sea surface, the acoustic received level data were transmitted back to the control center through the satellite, along with depth, navigation and conductivity – temperature – salinity data. This reactive behaviour was successfully demonstrated to a distance of up to 11.5 km from the acoustic source. The competence developed in this work will advance the technologies for underwater Intelligence, Surveillance and Reconnaissance missions**

Keywords—underwater glider; glider reactive behaviour; in-situ sonar performance assessment; glider acoustic payload; hydrophone equipped glider

I. Introduction

Operations in the maritime environment are strongly affected by the environmental knowledge, such as the properties of sea surface, water column and seabed [3]. Incomplete, uncertain, or incorrect environmental information about the area of interest can have a detrimental or even devastating impact on operations. Hence, the intelligence, surveillance, and reconnaissance (ISR) competences are key elements of NATO defense capabilities. Traditionally, most ISR activities are predominantly done by military vessels (including submarines) and thus area coverage is bounded because the operational monitoring platforms are limited in number. Moreover, it is inevitable that ISR activities are miniaturized in anti-access/area denial (A2/AD) regions for the same reason [4].

Autonomous underwater vehicles (AUV) have been recognized to have great potentials for assisting underwater counter A2/AD activities due to their maneuverability, heterogeneity in payloads, and low cost (compared to submarines) [5]. Underwater gliders are a kind of AUVs that are cost-effective, have very low power consumption hence long endurance (could be deployed as long as 221 days [6] or even longer), and suitable for long term ISR missions in a large area [7]. Increases in the reliability and capability of underwater gliders have made them attractive for both research and operations in the maritime environment, especially in sensitive regions.

The NATO – Science and Technology Organization – Centre for Maritime Research and Experimentation (NATO – STO - CMRE) has been developing novel payloads and smart sensing methodologies using different physical/chemical /biological properties in the water for increasing the capability of underwater gliders. This paper describes an application for underwater acoustic surveillance using a novel capability, i.e. glider reactive behaviour (GRB), which was implemented in a SLOCUM glider platform.

II. Motivation

Sonar performance prediction is usually accomplished through modeling efforts. It relies highly on two major factors, 1) the validity of the acoustic propagation model used, and 2) the quality (such as the completeness, correctness and uncertainty) of the environmental knowledge. In reality, due to the lack of environmental information and/or suitable acoustic propagation models, there is usually deviation between the measured and modelled quantities, such as transmission loss, acoustic received level (RL) and ambient noise level, that are crucial for sonar performance prediction. The deviation can be very large so that fatal conclusions could be made.

The motivation of this work is to enable an underwater glider to be an *in-situ* sonar performance assessment tool. Hydrophone/acoustic array equipped gliders are well suited for this application. For this purpose, the capability of gliders to react to signals of interest and then complete pre-defined missions is desirable. Gliders with acoustic payload and reactive behaviour capability are especially attractive for sonar

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predictions in A2/AD areas where environmental knowledge is insufficient. In terms of research, they may also be used to validate acoustic models, as well as to evaluate the impact of environmental knowledge on operational effectiveness at larger area coverage.

III. Implementation of Reactive Behaviours in Slocum Glider Platform

Glider missions (such as waypoints and trajectories etc.) are normally pre-programmed and uploaded to gliders before they are deployed. They are programmed to come to the sea surface periodically to re-position, and establish communications with the glider control center ashore to transmit observations and receive new missions via the iridium satellite links. Since the time between two adjacent glider surfacing events is usually several hours, the gliders may not able to report the observations of interest in a timely manner. Therefore, a way to intervene a glider mission while it is still in the water becomes even more important.

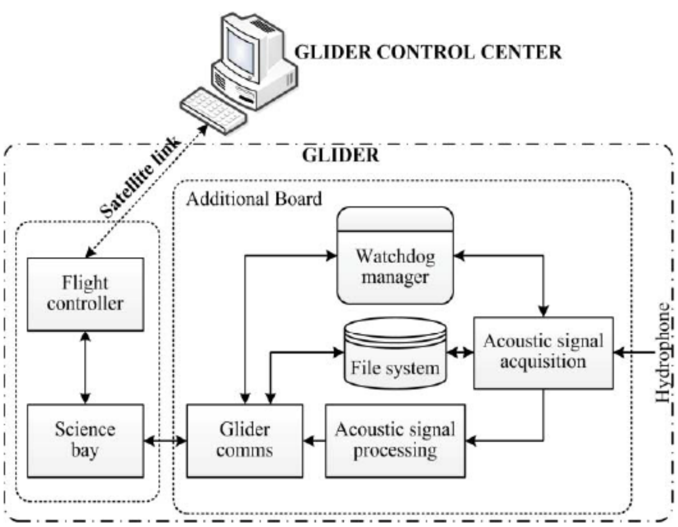

Fig. 1. Schemetic connections of the reactive behaviour system

A. *Reactive Behaviour System Framework*

A framework of glider reactive behaviour system that is capable of detecting acoustic signal of interest is shown in Fig. 1. It should be mentioned that the development presented in this paper is suitable for detecting other properties/events in the water if corresponding sensor(s), data acquisition system and signal processing module are mounted.

The 'Additional Board' shown in Fig. 1, also called 'additional computer' in the rest part of this paper, has integrated the most necessary components to fulfill the glider reactive behaviour system requirements summarized in section II.B.

B. *Basic Considerarions of Reactive Behaviour System*

To implement reactive behaviour capability in a glider platform, the following important requirements needed to be considered:

- The GRB system should be compact because of limited space in the science bay of a glider.
- A stable power supply for the GRB system is needed. Furthermore, the GRB system should have low power consumption due to limited glider power supply, and also for the reason to keep the long endurance feature of gliders
- The GRB algorithm for detecting the signal of interest should be fast to achieve real time onboard processing
- Enable the communications between the glider science bay and the GRB system (not available with the standard firmware from the glider manufacturer) so that positive detections can be passed to the glider flight controller, and to trigger pre-defined missions
- Not to intervene the procedure of continuously recording the acoustic signals on a hard drive at a request sample frequency (90 kHz during the sea trials)
- Keep tracking of the GRB activities, such as detection status, time and depth of a detection, acoustic RL (in dB), and signal to noise ratio (SNR) of the signal detected, and then save the information in files for future analysis

C. *Prototype Glider Reactive Behaviour System and the Test at Sea*

A prototype system for glider reactive behaviour was developed and implemented in a SLOCUM glider platform at CMRE in 2013. The fundamental goal was to identify the firmware requirements, and also with a special focus on establishing the communications between the GRB, science bay, glider flight controller, and an additional computer for acoustic signal processing. Since the main objective was to demonstrate the feasibility of implementing the GRB capability, a relatively simple detection scheme was chosen. The signal of interest was a broadband linear frequency modulated (LFM) pulse. A large pulse length and bandwidth product of the LFM pulse was chosen to ensure that the signal of interest would be easily detected. Essentially, an energy detector was employed for detecting the signal of interest, in which matched filter processing was the core algorithm. Moreover, the signals acquired by the hydrophone were sampled at a frequency of 4 kHz, and then shifted to base band for the efficiency of onboard signal processing.

TABLE I. Statistics of Acoustic Reactive Behaviour Experiment During MED-REP13

Attempt	Range (m)	Time Signal Transmission (Hrs:Min)	Time Surfacing (Hrs:Min)	Detection Yes/No	SNR(dB)
1	1555	13:21	15:28	Yes	NA
2	2606	13:42	15:49	Yes	29-32
3	3500	14:06	16:13	Yes	20-30
4	5100	14:35	16:42	Yes	16-23

The system was tested through simulations in lab, at sea during the MED-REP13 (Mediterranean – Recognized Environmental Picture 2013) engineering trial (July 2013) and also during the MED-REP13 cruise, which was conducted in the Ligurian Sea from 4th to 20th of August, 2013. The acoustic source was towed by NRV Alliance at different distances. A SLOCUM glider was programmed to undulate between 5 and 22 meters in depth, and to come to the surface as soon as possible upon the detection of the signal of interest. This reactive behaviour was successfully demonstrated on the 16th August, 2013, to a source – glider range up to 5.1 km. The statistics of the detections are listed in Table 1. The times in TABLE 1, and in all the figures and tables hereafter, are UTC (Coordinated Universal Time) times.

D. *Highlight of the Glider Reactive Behaviour System*

Encouraged by the accomplishment made in MED-REP13, some improvements in GRB hardware and software have been made in 2014 to meet the requirements (see section IV) for the measurements to be conducted during MED-REP14. The key components of the hardware and software of the GRB used in MED-REP14 are highlighted as follows:

1) Hardware:

a) Omni-directional hydrophone: An integrated acoustic sensors – Type JS-B100-C4DS-PA that is manufactured by J+S Limited [8]. The receive voltage sensitivity is -168 dB ± 1.5 dB re. 1V/μPa for a frequency band of 50Hz to 20kHz.

b) Acquisition board: The data collected by the hydrophone are then sampled using the CAS8 low power acquisition system developed at CMRE. CAS8 is capable of sampling 8 channels at variable sampling frequencies, ranges from 90 to 192 kHz. Data can be simultaneously written to files for archiving. They can also be made available through the network as a stream of TCP (transmission control protocal) packets.

c) Signal processing board: The processing board used in the glider acoustic payload is an IGEPv2 board developed by ISEE company [9]. It comprises a Texas Instrument DM3730 processor with an ARM Cortex A8 Core (1GHz) and a NEON SIMD co-processor.

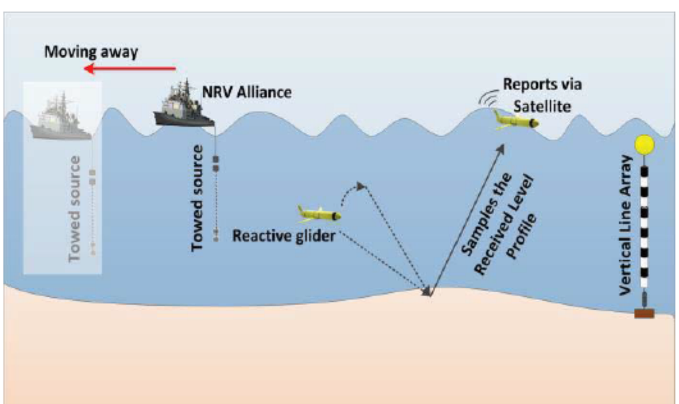

Fig. 2. A side view of the experimental geometry for acoustic received level measurements with glider based reactive behaviour

2) Software: The functions of the software are summarized as follows:

a) Establish a TCP connection with the CAS8 board to get the stream of data: CAS8 board provides a TCP server service to stream data on the network. Data are written into a FIFO implemented as a circular buffer.

b) Connect with the GLIEXCO application: GLIEXCO application runs on the IGEP. It provides an interface with SLOCUM science bay, such as getting navigation data from the glider and sending commands back to the glider, and also works as a mission manager.

The acoustic reactive behaviour study during MED-REP14 was carried out using glider *GRETA*. The experimental geometry is shown in Fig. 2. The water depth of the experimental site was around 170 m. *GRETA* was deployed near a 32-elelment reference vertical line array (VLA). The closest distance between *GRETA* and the VLA was around 500 m. The acoustic sources were towed by NRV Alliance. *GRETA* was programmed to fly back and forth in the vicinity of the VLA. The acoustic sources were towed to be at different distances from *GRETA*.

Fig. 3 shows two hydrophone equipped SLOCUM gliders. The one with hydrophone mounted to the tail of the glider is *GRETA*. It also has standard navigation and oceanographic payloads.

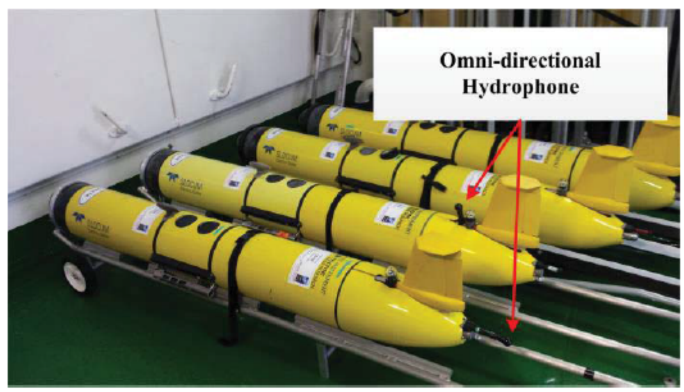

Fig. 3. Hydrophone equipped SLOCUM gliders

E. *Objective of the RL Measurement with GRB*

The objective of this test was to evaluate the improved capability of the hydrophone equipped underwater glider. The short term goal was to use a fleet of hydrophone equipped underwater gliders with reactive behaviour capability to monitor the acoustic environment continuously with an option to sample the acoustic vertical structure and report to the control center upon a trigger signal or signals of interest were detected. Specifically, the glider mission for this sea trial were:

- React to a more realistic acoustic signal (a set of line spectra to simulate the signature of a vessel) at different ranges (therefore different SNRs), and then conduct a simple mission:
    - Dive to user defined depth

  - Then sample the acoustic field and calculate the complex pressure at different depths continuously at the same time while coming back to the sea surface
  - Report and send the measured complex acoustic pressure along with depths, navigation, and CTD (conductivity – temperature - depth) data to the glider control center through the satellite
- Record the original acoustic data continuously on a hard drive mounted on the glider at the same time for other research topics. The sample frequency was 90 kHz for this study.

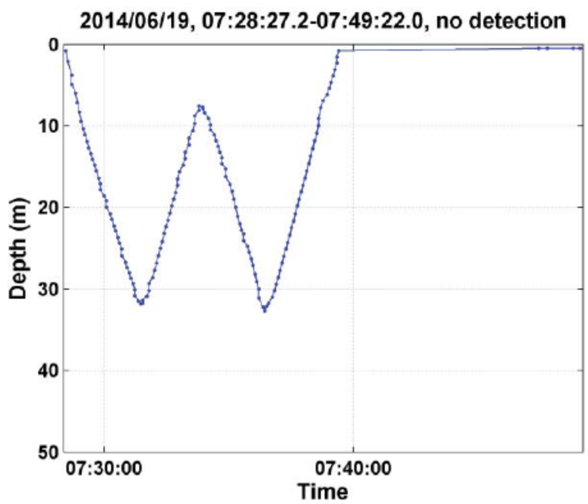

Fig. 4. The depth profile of *GRETA* during the test runs: no detection

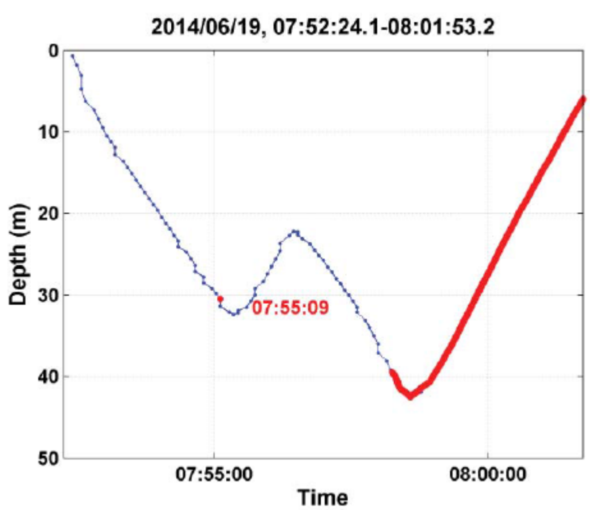

Fig. 5. The depth profile of *GRETA* during the test runs: positive detection. The red line indicates the glider trajectory when acoustic received levels were processed and recorded in real time. The text in red is the time when the signal of interest was detected.

F. The Experiment

The acoustic reactive test was conducted twice. The first one took place in the afternoon of 13 June. *GRETA* did not perform as expected due to an inappropriate detection threshold and setup. The problem was investigated and solved by the glider development team both onboard and ashore.

Another time slot was allocated for the glider reactive experiment on 19 June. Four dives were conducted first to test the revised detection/reactive algorithm of *GRETA*, two for the false signals and two for the true signals.

During the test runs, *GRETA* was programmed to dive between 7 and 30 meters depth. If there was no detection, the glider would finish one 'W' shaped run and then come back to the surface. If there was a positive detection of the signals, the glider would change its original track and dive to a depth of 40 meters depth, and then sample the vertical structure of the acoustic field while it was coming back to the sea surface. Immediately after it reached the surface, *GRETA* would pack the navigation, detection status, complex acoustic pressure, and CTD data and send them to the control center at CMRE. The depth profiles of the test runs are shown in Fig.4 (no-detection) and Fig.5 (positive-detection).

The formal glider acoustic behaviour experiment was conducted from noon of 19 June, immediately after the test runs.

GRETA was programmed to glide over a distance of approximately 500 m from the reference VLA. It was set to dive continuously between 5 and 160 meters under the sea surface during the detecting mode.

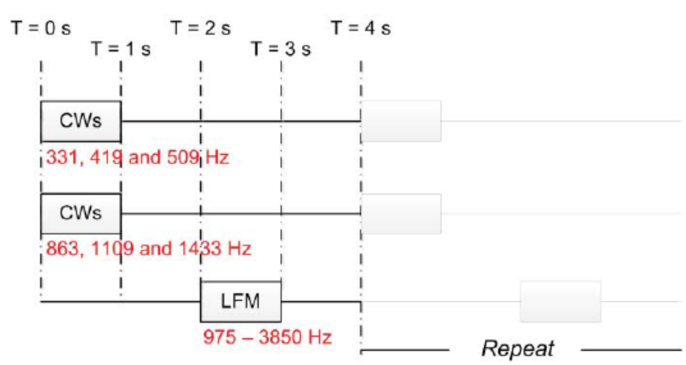

Fig. 6. Description of the acoustic signals being transmitted at active acoustic stations.

TABLE II. SIGNATURES OF THE SIGNAL TO BE DETECTED

No.	Frequency (Hz)	SL (dB re 1μPa @ 1m)
1	509	182
2	863	185
3	1109	186
4	1433	183

The acoustic sources were towed by NRV Alliance and stopped with stations at different distances from the bottom moored acoustic arrays. A combination of CW (continuous wave) and LFM pulses were transmitted during the Alliance transit, as shown in Fig. 6. The signature and source level (SL) of the signal to be detected are listed in TABLE II. The experiment was terminated due to the scheduled recovery and deployment for other measurements.

An example of real-time acoustic received level measurement with glider-based reactive behaviour is depicted in Figs.7 and 8. The locations of the acoustic receivers, sources and glider *GRETA* are shown in Fig. 9. The red dots indicate the source positions when the acoustic signal of interest was detected. The maximum detection range between the source and glide *GRETA* was 11.55 km. The source-glider range and the times of the signal of interest was being detected are summarized in TABLE III. The received level profiles, triggered by the signal of interest, as a function of time and depth are shown in Fig.10.

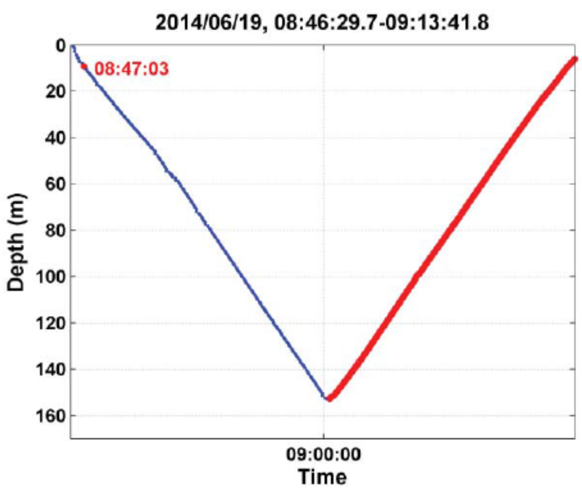

Fig. 7. Depth profile of *GRETA* during the formal runs for acoustic received level measurements. The signal of interest was detected at 08:47:03. The red line indicates the glider trajectory when acoustic received levels were processed and recorded in real time.

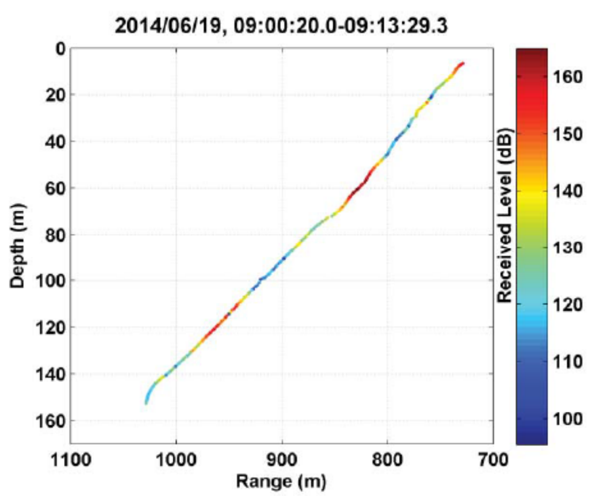

Fig. 8. Acoustic received level for 1433Hz CW pulse as a function of range and depth collected by *GRETA*, corresponding to the red trajectory shown in Fig. 7.

IV. Summary

In-situ acoustic received level measurements with glider based reactive behaviour were successfully conducted during the MED-REP14 sea trial. The goal of this development was to test the feasibility of a hydrophone equipped glider as a mobile virtual vertical mooring for sampling the acoustic field as a function of range and depth. Acoustic data collected by gliders with such capability can be used, just to mention a few, to characterize the seabed using anthropogenic sound (such as active sources and shipping noise), for ISR missions in A2/AD region, for *in-situ* sonar performance assessment, and for validating sonar performance prediction.

The capability of a hydrophone equipped SLOCUM glider with reactive behaviour system was proven twice at sea to have great potential for further exploitation, and for wider implementation of the reactive behaviour system in more SLOCUM gliders.

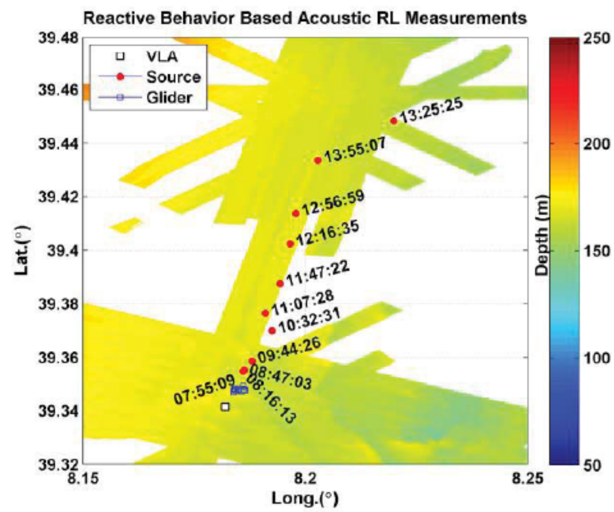

Fig. 9. Geometry of the *in-situ* acoustic received level measurements with glider reactive behaviour capability. The red dots are the acoustic source locations, the text in black near the red dots are the times when the signals of interest were detected. The color background is the bathymetry collected by the shipborne multibeam swath system.

TABLE III. Statistics of Positive Detections of *In-Situ* Acoustic Received Level Measurements with GRB During MED-REP14

Attempt	Range (m)	Time of Detection (Hrs:Min)
1	624	07:55:00
2	798	08:16:13
3	860	08:47:03
4	1234	09:44:26
5	2503	10:32:31
6	3200	11:07:28
7	4512	11:47:22
8	6147	12:16:35
9	7522	12:56:59
10	11547	13:25:25
11	9639	13:55:07

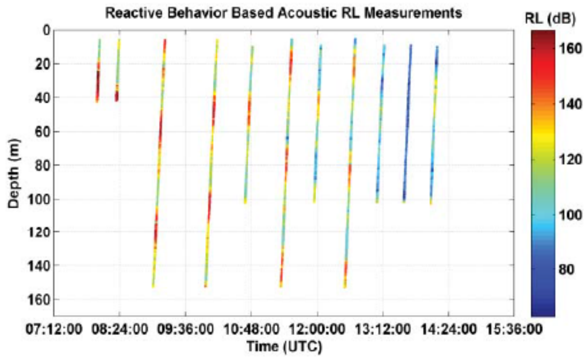

Fig. 10. Acoustic received level profiles as a function of depth and time. Only one of the line spectra of the signal to be detected, 1433 Hz, is shown as an example.

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