Ocean gliders payloads for persistent maritime surveillance and monitoring

A.Maguer, R.Dymond, A. Grati, R.Stoner, P.Guerrini, L.Troiano, A.Alvarez
NATO Centre for Maritime Research and Experimentation (CMRE)
La Spezia, Italy

Abstract—**Due to their long endurance at sea, underwater gliders are envisioned to play a significant role in persistent maritime surveillance and monitoring. However, so far they have been mainly used for measuring sea water properties such as temperature, salinity and optical properties. CMRE is considering using gliders for different new missions such as passive acoustic monitoring, sea bottom and sea surface characterization as well as service as an underwater or surface node in a distributed heterogeneous autonomous vehicles network. This paper describes the effort made at CMRE for developing and assessing the new payloads necessary for fulfilling those new missions. Hence, a comprehensive description of acoustic, environmental characterization and communication glider payloads is given in the paper. Results obtained at-sea with the use of the different payloads are briefly mentioned and demonstrate great enhancement capability for the gliders.**

Keywords— acoustic, AUV, glider, Wave Glider, towed array, acoustic communication, gateway buoy, wave estimation, maritime

I. Introduction

Gliders are autonomous vehicles propelling themselves through the ocean for a long period of time, either by changing their buoyancy for the underwater glider or by taking advantages of the environment as the Wave Glider exploits waves from the ocean. The gliders offer capability for persistent surveillance and monitoring of the underwater environment. Gliders have been demonstrated to be a cost efficient solution to the measurement of seawater properties such as temperature, salinity, and optical properties. To date, their potential as a discreet and cost-effective means to perform other missions is still under investigation, requiring much larger energy capability than the most common oceanographic glider applications which are based on low power sensors such as CTD and optic sensors.

This paper describes the effort made at CMRE to increase present capabilities of underwater/surface glider technology in order to address potential applications including acoustic passive monitoring, survey seafloor properties estimation, and communication across the sea-air interface between unmanned and/or manned system as well as environmental monitoring such as sea-state wave measurements. This paper also describes the effort that was made at CMRE for the development of these new payloads.

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The first section of the paper describes the development of different acoustic monitoring systems that were integrated in CMRE gliders. They were designed to address different fields of application such as passive monitoring of the underwater environment and also for marine mammals risk mitigation purposes. For the first purpose, the European community has a willingness to ensure that any human action which introduces energy, including underwater noise, is at levels that do not adversely affect the marine environment and therefore is looking for technical means to monitor noise. Other acoustic applications are the detection of small surface vessels in harbor protection, autonomous nodes for anti-submarine warfare as well as investigating seabed characterization by the use of underwater ambient noise (sea surface generated noise and distant shipping). This paper describes the different acoustic payloads that have been designed, built and tested over the last five years for covering those applications. They are composed of single hydrophone, volumetric array or towed array of hydrophones. They all incorporate specific custom made low-power and high-data-capacity data acquisition systems, as well as embedded real-time processing capability for some of them. Such data acquisition systems, with different characteristics, currently exist but are unfortunately not always commercially available and/or do not exactly meet CMRE requirements. Finally, this section gives, for the different applications, the obtained at-sea that successfully demonstrates the potential of gliders for long-term, other than oceanographic, acoustic characterization and monitoring missions.

The use of glider technology to optimize communications between unmanned and/or manned systems either underwater or above water is described in the second section of the paper. It covers the work done by CMRE which, in addition to the development of gateways buoys that are moored, also considers using the Wave Glider as a mobile platform equipped with an underwater modem and an RF link for ensuring data transfer between its fleet of Autonomous Underwater Vehicles (AUVs) and manned platforms during an ant-submarine exercise. The Wave Glider equipped with an Evologics modem was particularly useful during an exercise in February 2013 as a mobile gateway node. It accomplished this function becoming the most used acoustic communication channel for the OEX-C autonomous underwater vehicles. Navigation and station keeping features were satisfactory and energy storage on board permitted continuous operation for more than 8 hours per day.

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Finally, the third section describes the use of gliders for estimating sea-state conditions when surfaced. For this purpose, a wave payload was developed at CMRE for estimating in real-time wave height and amplitude from a glider. The payload, based on the use of a set of accelerometers, is described and measures the glider motion in response to the wave field. At-sea results of the data measured and the wave parameters estimated through the use of a payload are given and compared to measurements that were done with a more conventional wave rider.

II. ACOUSTIC PAYLOADS

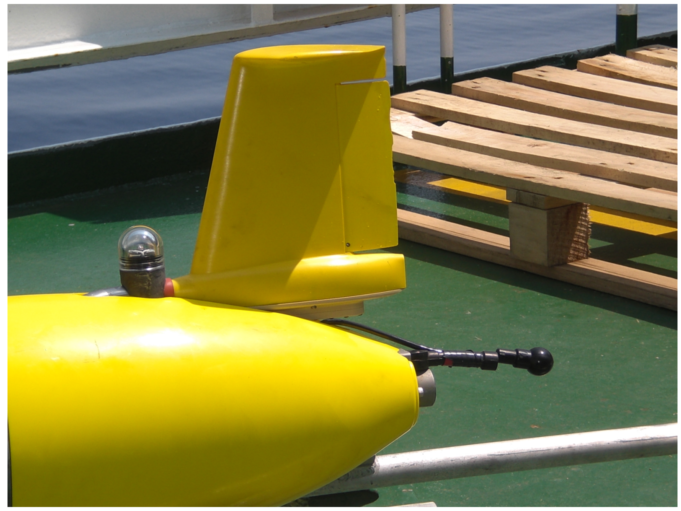
This section describes all the different acoustic monitoring systems that have been integrated in CMRE gliders in order to address different fields of application such as passive monitoring of the underwater environment, marine mammals risk mitigation purposes and sea bed properties characterization.

A. Single hydrophone array payload

The first payload built at CMRE in 2010 is a single hydrophone payload that was developed having as first objective the capability to perform real-time detection and classification of marine mammals with a glider. The work was performed in collaboration with the Technical University of Catalonia (UPC) leveraging on their work done in the marine mammals' field for many years.

The original system [1] that was developed was capable of simultaneously recording up to 2 acoustic channels, with 24 bits resolution, sampled up to 192 kHz and had a 1TB disk capacity. It allowed continuous Detection/Classification DC processing with endurance from 4 to 9 days depending if one or two channels are recorded. The processing capability is provided by an Intel® Atom™ Z530 processor. Special care in the design of the complete system was given to achieve low-power consumption that is a mandatory requirement for running multi-day missions. It must be noted that this payload was designed in a first attempt to demonstrate the feasibility of performing both real-time acoustic DC processing within a glider. Fig. 1 displays how the hydrophone is mounted on the glider and shows the electronics hardware. The hydrophone is a low noise pre-amplified spherical hydrophone from the Company J&S.

The payload integration into the Teledyne/Webb glider has been challenging due to the small amount of space available within the glider. The hydrophone was mounted as shown on Fig. 2 below on the stern of the glider. The zoomed picture of the stern in Fig. 1 (top) shows the mounting of the hydrophone. The middle part of the glider is the payload into which has been integrated the acoustic payload.



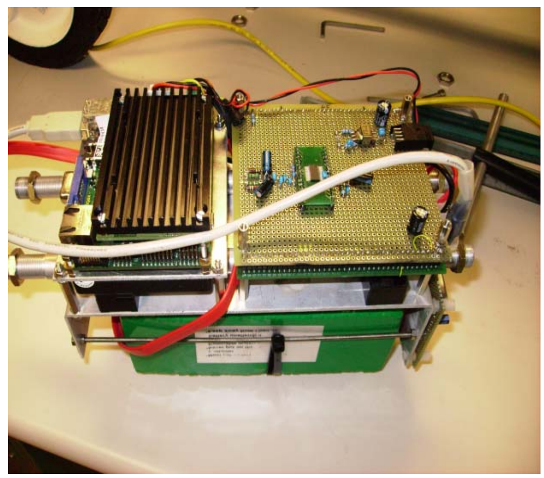


Fig. 1. Hydrophone mounting on glider (top) and acoustic payload electronics (bottom)

The analysis of the at-sea data have shown very high quality acoustic data when the glider is gliding in the water column. However, high noise was measured when the glider was on the surface due to splashing water or the hydrophone bouncing on the surface. Noise peaks were also measured during engine operation. The capability of the system to detect/classify marine mammals in real-time within a glider was succesfully demonstrated at sea [1]. Based on the high quality of the collected acoustic data, CMRE believes in glider capability to perform acoustic monitoring missions. It is also believed that the acoustic payload integrated in the glider could provide her with the capability to detect potential surface vessels that could be a threat when surfacing. CMRE is working on the detection processing chain that would allow alerting the glider of any potential surface threat and even more adaptively change her mission, for example preventing her to surface.

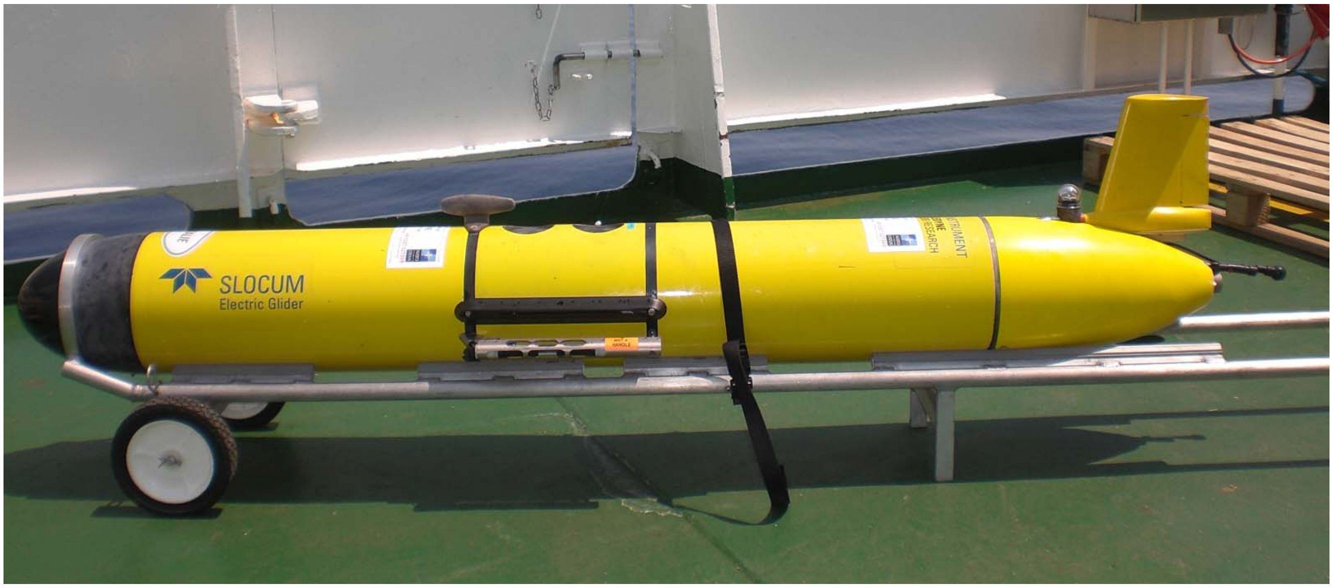


Fig. 2. Teledyne-Webb glider with acoustic payload in the middle and hydrophone behind the tail

Furthermore, since the initial development of this payload a new 8-channel data acquisition system has been developed at CMRE. This system was designed within the framework of the HYDRA buoy [2] that was developed at CMRE in 2011 for performing long endurance passive acoustic monitoring systems. The system was also designed at that time with dimensions compatible with the size of small AUVs or gliders. CMRE future work will be dedicated to the enhancement of the one hydrophone system by integration of a hydrophone array in the glider.

B. Towed array payload

The second acoustic payload described is a towed array payload that was developed to assess new concepts of operation in anti-submarine warfare (ASW). The new concepts were based on the use of autonomous underwater vehicles (AUVs) equipped with towed arrays [3]. For this purpose, CMRE began in August 2007 to design and build a thin diameter (31 mm) high-frequency nested towed array (See Fig. 3). The array is described in [4] and since then has been extensively towed by the 21” OEX-C Explorer.

Currently, the ASW program at CMRE is simultaneously using two AUVs with towed arrays to perform multi-static operations. A demonstrated capability was observed in some specific operational scenarios as described in [5].

Over the years, CMRE has undertaken several modifications to the original towed array in order to enhance its performance by providing left/right ambiguity soling (through the use of triplet hydrophones) as well as in reducing its size and power consumption for use of smaller autonomous vehicles.

This section describes the towed array that CMRE developed in 2012 for being towed by a small AUV or a glider. The array is a thinner array diameter (18mm) which was created to reduce the drag of the array to the vehicle and therefore able to be used by smaller AUVs and gliders currently on the market.

Fig. 3. BENS array attached to OEX-C AUV before its deployment at-sea from ALLIANCE

In addition to the reduction of the diameter to reduce drag, the SlimBENS array was specifically designed to reduce the overall power consumption, as this factor is critical for its integration with smaller vehicles that have low energy capacity. Therefore array power consumption was reduced to 0.7W, compared to the more traditional CMRE array which consumes 9.5W. The array has an external diameter of 18mm, a total length of 25.7m and is composed of 46 channels. The array has 3 sets of Non Acoustic Data, (NAD), multiplexed onto a single serial LVDS Data Stream. The array is compatible with the existing OEX / BENS towing and acquisition system.

Fig. 4 shows part of the SlimBENS array as compared with the 31mm BENS array, as well as a triplet hydrophone used for the left/right ambiguity solving.

In addition to reducing the size and the power consumption of the array, CMRE invested in 2011 in the development of a low-power data acquisition system with the scope of increasing the endurance of AUV mission while equipped with the SimBENS array. The endurance is a key issue for developing persistent underwater autonomous surveillance as explained in [6].

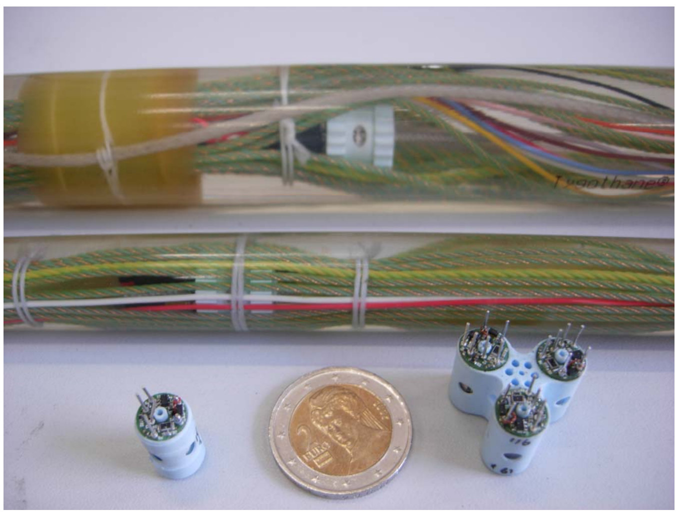


Fig. 4. BENS towed array (top) with SlimBENS array (down). Both hydrophone and triplet hydrophone are shown.

The data acquisition board is shown on Fig. 5.

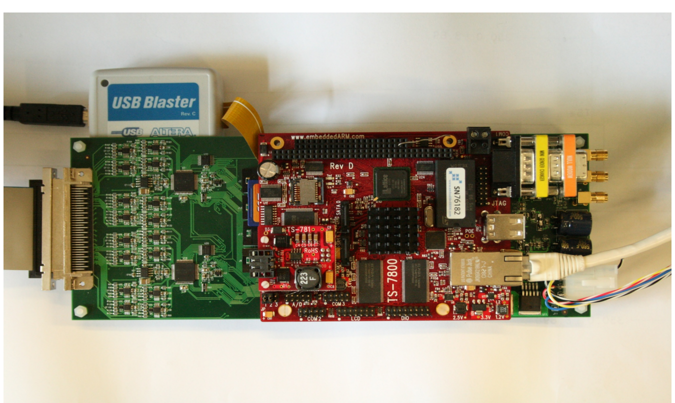


Fig. 5. 32-channel data acquisition board.

The architecture of the designed acquisition system (see Fig. 5) was portioned in different sub-modules providing the flexibility required in different employment scenarios. The power module, timing module and analog front-end are application dependent. The Acquisition Module (AM) and the Single Board Computer are designed to be easily reutilized in many applications. The system uses 24-bit Sigma-Delta Analog-to-Digital converter and provides the capability to simultaneously acquire 32 channels. It was designed specifically to address low power applications. Low power consumption, of the order of 16W, was achieved for the recording of 32 channels at 144 kHz sampling frequency. Once developed, this performance was much lower than the power consumption of existing systems available on the market and lower than the existing system on-board OEX-c that was of the order of 40W.

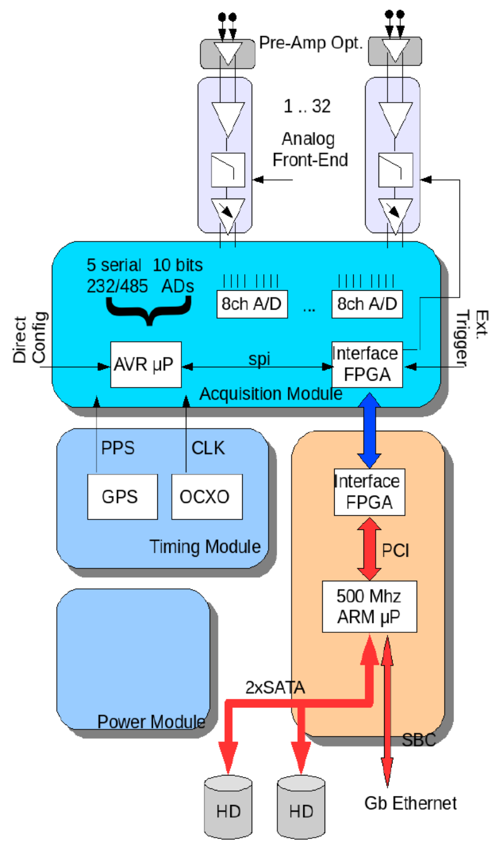


Fig. 6. 32-channel data acquisition architecture.

The data acquisition system has not yet been implemented in an AUV or a glider. However, CMRE is considering performing this integration in 2014

C. *Volumetric array payload*

The purpose of this last acoustic payload is to transition a methodology of using underwater ambient noise (sea surface generated noise and distant shipping) for seabed characterization to an autonomous vehicle equipped with a tetrahedral and vertical array. This payload was also designed for performing small surface boats localization. The vehicle in subject is the newly developed hybrid glider/autonomous underwater vehicle named eFOLAGA [7] which has the advantage over ordinary gliders of more flexible maneuverability features, i.e. the vehicle can operate in either glider or ordinary propulsion mode. The eFolaga, equipped with the volumetric array, is shown in Fig. 7.

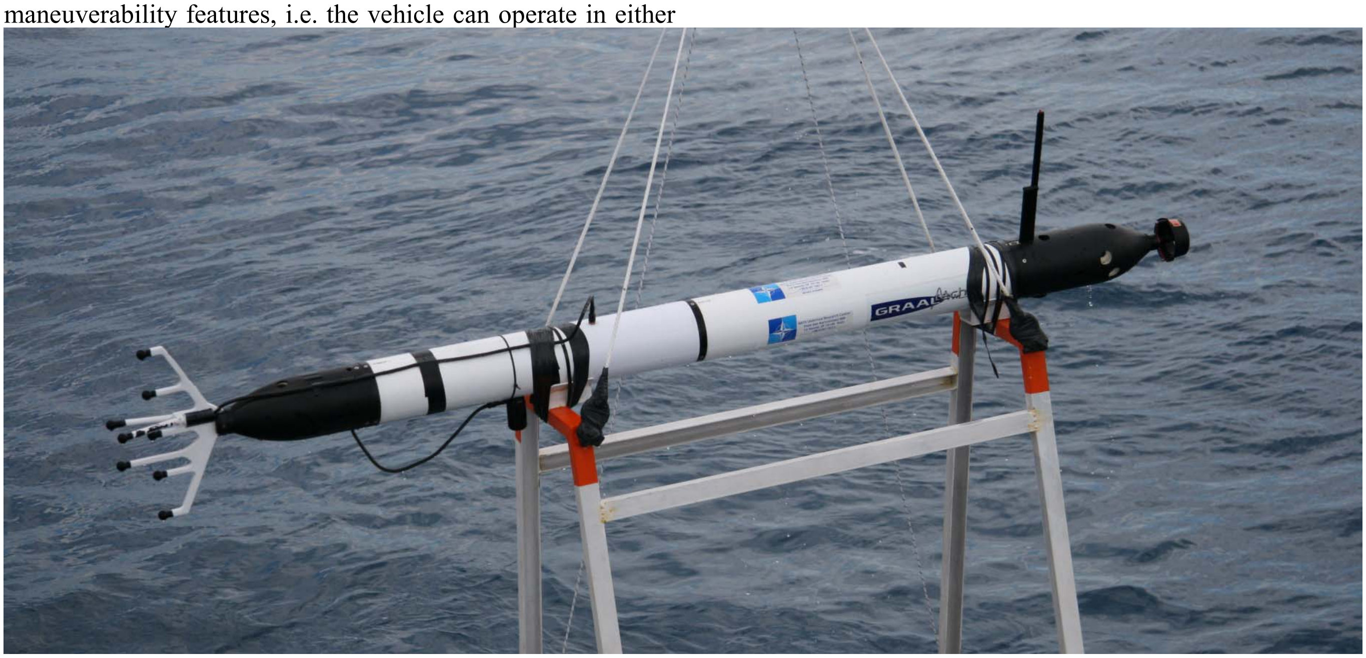


Fig. 7. eFolaga hybrid AUV/glider equipped with volumetric array payload. It is mounted on a bottom-moored frame for fixed position acoustic measurements

The eFolaga array is show in Fig. 8 and consists of eight elements; five in a vertical configuration, and three offset from the center element to form a tetrahedron with the center element. The spacing between the vertical elements, as well as lengths of each edge of the tetrahedron, is 10 cm.

Fig. 8. Volumetric (tetrahedral and vertical) array of the eFolaga.

The acquisition system used for the volumetric array payload is the 8-channel data acquisition system of the HYDRA system. The hydrophone used is the same as the ones used in the single hydrophone acoustic payload.

The GLASS'12 experiment was conducted in July 2012 off the coast of northern Italy near La Spezia. The purpose was to investigate potential uses of an AUV affixed with a nose-mounted array.

Most of the acoustic data analyzed from the sea trial was acquired while the eFOLAGA was mounted on the bottom-moored frame. All electronic devices for navigation purposes were turned off and only the data acquisition system was active. Some attempts were made to keep the vehicle at fixed depths by manually trimming the buoyancy, and to perform a linear track at constant depth using the propeller for forward motion. However, the behavior of the vehicle was not as expected and only the bottom-moored missions were considered.

a) Small surface ship detection results

A small rubber boat with an outboard engine outfitted with a portable GPS data recorder maneuvered in the vicinity of the array. It was detected [8] through advanced processing of the volumetric array demonstrating that compact volumetric arrays are effective tools for the detection of small surface craft. The extent of their potential usefulness has yet to be determined as the mobile AUV platforms to which they can be mounted could make them strong assets for remote monitoring activities.

b) Bottom characterization results

The eFOLAGA was bottom mounted on the frame and used on two different sea bottom types (sand and mud). The seabed reflection coefficients for both sites were estimated by dividing the downward beam intensity with the upward beam intensity obtained from conventional plane-wave beamforming. Sub-bottom profiling were also computed and compared to profiling obtained by the towed EdgeTech SB216S. Both reflection losses and sub bottom profiles were found very close to the ground truth [8].

Overall, the results demonstrated the capability of using autonomous equipped with a unique vertical line and tetrahedral compact acoustic array for estimating seabed properties in a cost- and time-efficient manner. However, CMRE is investigating for 2014, the integration of a larger array either on the eFolaga or more probably on a Teledyne Webb glider that would provide better vertical resolution and therefore better results.

III. SEA/AIR COMMUNICATION PAYLOADS

CMRE decided in 2012 within its ASW program to investigate the capability of providing persistent communications across the sea/air interface. For this purpose, in addition to the development of gateways buoys that are moored, the Liquid Robotics Wave Glider was considered as a mobile platform equipped with an underwater acoustic modem and a RF link for ensuring data transfer between the AUVs and manned platforms or labs on the surface (Fig. 9).

The Centre has designed a payload for the Float dry-box to use the Wave Glider as a mobile gateway with a wireless link and an underwater acoustic modem. The Wave Glider payload is mainly composed of an acoustic modem with Ethernet interface, an IGEP II card and a 25.9V 12.6 Ah rechargeable lithium-ion battery, a GPS receiver with 1pps output, an Ethernet radio and Ethernet switch, a PIC board with RS 232 interface to monitor battery voltage, battery current, internal pressure and 4 port RS232 to USB interface for the GPS receiver, Wave Glider control interface. Fig. 10 shows a picture of the payload electronics.

With this configuration the Wave Glider payload can be used as a simple bridge between the radio and the acoustic modem to send commands from a surface vessel to an Underwater Vehicle or the software (based on MOOS or ROS) installed in the IGEP card can use the acoustic modem and send commands to the Wave Glider without radio communication. The payload battery is necessary to provide the peak current for the acoustic modem and it is recharged by the solar panels of the Wave glider.

Fig. 9. Wave Glider equipped with Evologics underwater mode. On deck (top), just deployed (bottom left), and with Evologics modem attached to wing (bottom right)

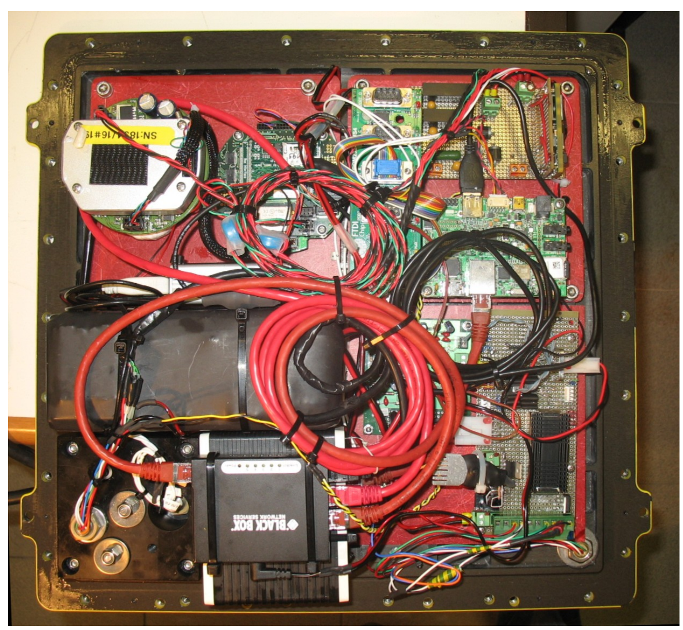
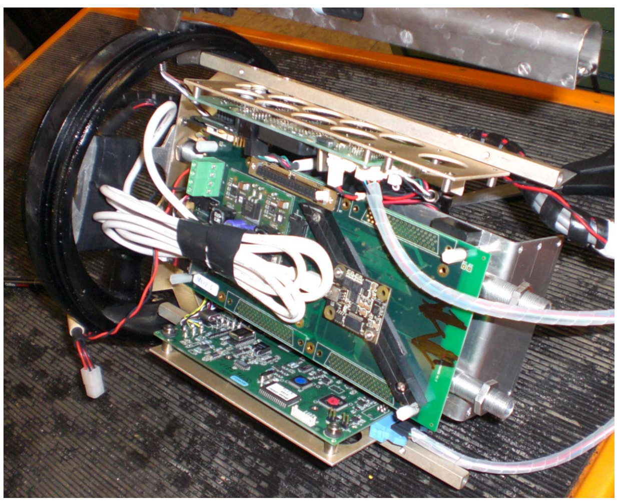


Fig. 10. Wave Glider modem electronics payload

The Wave Glider was extensively useful during the Proud Manta Exercise in February 2013 as a mobile gateway node. It perfectly accomplished this function becoming the most used acoustic communication channel for the underwater OEX-C vehicles. Navigation and station keeping features were satisfactory; energy storage on board granted continuous operation for more than 8 hours per day.

IV. WAVE ESTIMATION PAYLOAD

The last payload described in this paper has been developed for extracting information about the on-site directional wave spectra that could be obtained from glider response measurements on the sea surface. The glider was equipped with a 1056_0 - PhidgetSpatial 3/3/3 package [10] and associated data logger and control unit, to record the platform motions when she is on the surface as show in Fig. 11.



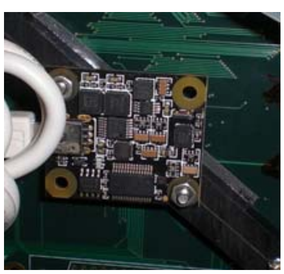


Fig. 11. Wave estimation payload. Full payload Hardware (top), IMU/Gyroscope//accelerometers/compas Phidget spatial 1056 sensor package (bottom)

The PhidgetSpatial 3/3/3 is composed by an inertial measurement unit (IMU) that measures accelerations up to ±5g and angular rotations up to ±400^{o} per second in 3-axes and a compass that measures magnetic fields up to ±4 Gauss in the same axes. The body-fixed axes were defined with the positive *x*, *y* and *z* axes in the bow, starboard and downward directions, respectively. Samples were acquired every 16 ms. Records were segmented into 30 minutes during a 2 hour sampling period. To enable future comparisons with a reference, the glider was deployed at 0.85 Km distance from a Datawell Waverider MkIII [11]. A data processing pipe-line was implemented in delay mode to assess the non-directional sea state conditions from the recorded glider vertical accelerations.

Data were resampled at 4Hz to avoid asynchronous records generated by the acceleration detection threshold of the IMU. Next, the 30 minutes record was further segmented into segments of 300 s. Then, the mean value was removed and a spectral leakage reduction using a Hanning window performed over each segment. The Power Spectral Density (PSD) was then computed using a Fast Fourier Transform. At the low frequency end, accelerations become very small and disappear in the sensor noise. Therefore, a digital high-pass filter with a cut off at 20 s is applied. The final PSD is obtained as the average of the spectral densities obtained for the different segments. The PSD of vertical accelerations is transformed into a PSD in vertical motions in the frequency space to derive some standard parameters like the significant wave height (H_s), mean period (T_1) and zero up-cross periods (T_2).

A field experiment was conducted in March 2013 offshore La Spezia (located on the northwestern coast of Italy) to test the capability to infer sea state conditions from a Slocum glider. Parameters derived from the glider motion slightly overestimate those reported by the wave rider. In all parameters, differences are below 5 % of the estimated value.

These results reinforce the initial hypothesis that sea state conditions could also be provided by glider platforms. Further research to estimate directional properties of the wave field from gliders is still ongoing.

V. CONCLUSIONS

This paper has described several payloads that have been developed at CMRE for enhancing the glider capability and better preparing their future use in new concepts dealing with persistent autonomous surveillance and monitoring. All the payloads developed have been extensively tested and used at-sea. Significant results were achieved that validate the use of gliders for operations outside the oceanographic world in which they have been mainly used so far. Further work will be dedicated to better assess the performance achieved with those payloads and derive any potential enhancements that would be necessary for achieving operational use of the glider technology for NATO missions.

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