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NOC Liverpool report for the miniSTABLE benthic
lander deployments as part of the
UK-SSB research programme

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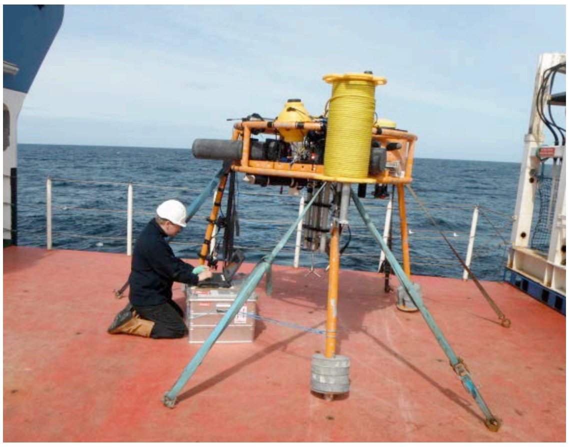

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ABSTRACT

A review of the key features of a series of seabed based scientific lander deployments undertaken by the National Oceanography Centre at Liverpool, UK as part of the UK Shelf Seas Biogeochemistry (UK-SBS) Programme (www.uk-ssb.org) is provided in this document. A bespoke lander design provided a unique platform for a broad range of scientific measurements to facilitate novel benthic or near seabed scientific research. A complex and diverse set of lander based instrumentation included dissolved oxygen flux or 'eddy correlation' sensors, sonar based localised seabed distance and contour profiling, high resolution water velocity measurements and measurements of suspended particulate matter in the lower water column. The sensor suite was complimented by an automated, water sampler for collecting and preserving samples with a programmable sample volume and collection time. These seawater samples were suitable for determining dissolved inorganic nutrient levels close to the seabed. Inline filters were used to assess the levels of particulate concentrations at the time of each sample collection. A series of scientific survey cruises, using the research vessel RRS Discovery, occurred from March 2014 to September 2015 as part of the UK-SSB programme. Within this sequence of scientific cruises four key Celtic Sea based sites were surveyed. The lander deployment sites used provided a diverse range of seabed based scientific study conditions.

KEYWORDS:

ISSUING ORGANISATION
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Terms and Definitions

miniSTABLE	A compact version of the Sediment Transport and Boundary Layer Experiment (STABLE) series of seabed based scientific lander systems. These landers are basically metallic frames used to provide a platform for deploying sensors and systems to support scientific research. Options exist to use moorings, ballast and recovery systems to aid the operational use of the lander from research vessels. The term miniSTABLE refers to a version of the series of benthic landers produced by NOC Liverpool that is approximately 2 metres tall and 2 metres in diameter.
Eddy Correlation	A technique involving high frequency underwater measurements a short distance above the seabed (typically 10–50cm). The aquatic eddy correlation or eddy covariance technique described in this report uses high frequency dissolved oxygen concentration and vertical water velocity measurements to determine by averaging the flux or flow of oxygen to or from the water to sediment interface close to the seabed.
RRS Discovery	Royal Research Ship Discovery is a scientific research vessel owned by the UK Natural Environment Research Council (NERC) that went into service in 2014. The ship is 99.7m long, has a beam of 18m, it has a crew of 24 people and up to 28 scientific berths, with an operational endurance of up to 50 days.
NIOZ Corer	This apparatus, usually in the form of a rectangular frame, is lowered over the side of a ship to the seabed to extract sediment samples. The system is able to take samples typically up to 500mm diameter or 500m square, usually up to a sample depth of approximately 500mm. Ballast weight may need to be added to this type of seabed core extraction apparatus to achieve the require core extraction depth.

Abbreviations

UK-SSB	The UK Shelf Seas Biogeochemistry programme (www.uk-ssb.org)
NOCL	National Oceanography Centre, Liverpool, UK
CEFAS	Centre for Environment Fisheries and Aquaculture Science
ROV	Remotely Operated Vehicle
CTD	Conductivity, Temperature and Depth sensor
ADCP	Acoustic Current Doppler Profiler
UV	Ultra Violet
ROV	Remotely operated vehicle
GPS	Global Positioning System
GMT	Greenwich Mean Time

Contents

1. Scientific survey motivation and objectives

Shelf seas provide a habitat for a diverse range of ecosystems and usually have relatively shallow waters of up to 100s of meters in depth. This can offer a more commonly used diverse marine life resource for fishery activity than that that of the relatively inaccessible deeper oceans or seas. Although many scientific studies of shelf seas have been conducted to date the physical biogeochemical processes involved, in general, remain poorly understood. Factors such as carbon storage, dissolved nutrient cycles and how shelf seas interact with open oceans, the subsequent impact on the related marine ecosystems and the environmental effects of air to sea temperature exchange remain areas of key scientific interest and research. An improved understanding of the consequences of human activities with respect to shelf seas such as fishing, pollution, offshore energy generation (e.g. wind farms and tidal based generators) can all have an effect on the environment and the resident ecosystems. Studies relating to the consequences of human activity and climate change represent key motivators for undertaking this research. The advancement of the understanding of these processes will help to provide the basis for improved predictive models of key factors such as ecosystem prevalence and water quality. This in turn will provide an improved reference for environmental management and policy determination.

The UK-SSB programme (www.uk-ssb.org) was devised to take a broad ranging or holistic approach to studying the cycling of carbon and nutrients for the UK and European shelf seas, combined with the effect on primary production of simple organisms via photosynthesis, and secondary production involving the transformation by biomass consumption of organisms into different or more complex forms. The interaction mechanisms at the interface between shelf seas and the open-ocean and air sea interaction, particularly with respect to greenhouse gasses, are areas of key interest e.g. carbon dioxide release or absorption.

Incorporated within this broad range of study the National Oceanography Centre at Liverpool, UK (NOCL) has devised a seabed based lander system with a complex and diverse suite of scientific measurement systems. The general goal has been to provide high resolution measurements of some of the physical properties in the benthic or near bottom regions of the underwater column. These include the water velocity, vertical dissolved oxygen flux, underwater sediment properties, sediment motion or transport and autonomous water sampling for dissolved nutrient measurements. The sensor suite used also includes a laser based holographic imaging system for determining suspended sediment particle sizes and concentrations. The high resolution measurements generated by the lander are intended to compliment more traditional approaches to surveying such as physical sampling and the use of ship based measurement profiling systems.

Within the UK-SSB sequence of research cruises from March 2014 to September 2015 a series of key areas for studies of seasonal cycles or change were targeted for a one year period of study. A sub-set of these cruises focussed on studying the benthic or near seabed properties at the four key survey areas that are shown in fig. 1. The box shaped seabed based survey locations were areas bound by GPS coordinates that were typically 1-2km x 1-2km.

Seabed sediment collection at each of these survey sites has identified the general consistencies and sediment properties as summarised in Table 1. This information is based upon the preliminary results from the analysis of seabed core samples collected during the

RRS Discovery based DY008 research cruise from 18th March to 11th April 2014, as part of the UK-SSB research programme.

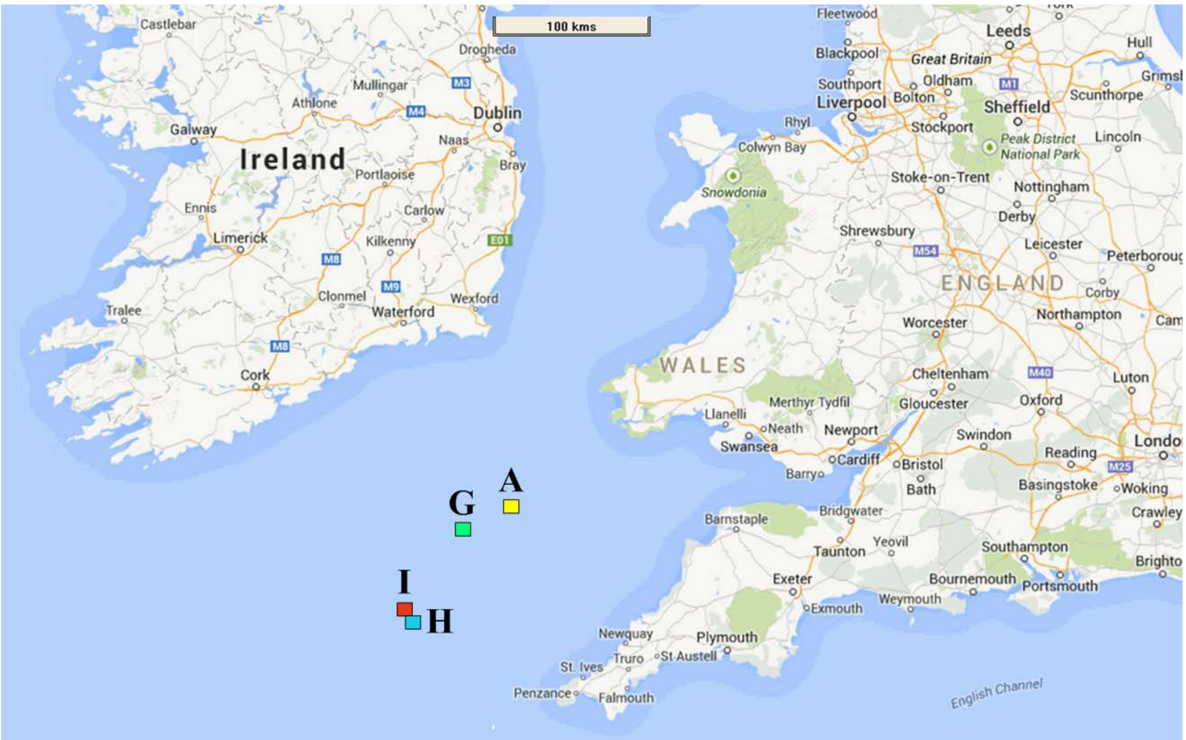


Fig. 1. The benthic A, G, I and H scientific survey site locations

Possible changes in sediment consistency over time or seasonal change are not taken into account with this initial data analysis. The information in table 1 is intended to provide a guideline as to the likely seabed or close to seabed properties that may be encountered at these study areas. As such this information is intended as general reference when planning a scientific seabed based lander deployment. A more detailed review of the scientific survey sites seabed based sediment consistency is provided in appendix A of this document.

Table. 1. The benthic A, G, I and H scientific survey site sediment properties

Survey site	**Sediment Density** (dry in Kg/m3 up to 5cm depth)	**Sediment Mean Grain Size** (μm)	**Sediment description**
A	600-850	20	Fine scale mud with some sand
G	1400-1600	1000	Predominantly sand
I	1100-1300	30-50	Sandy with some mud
H	1200-1300	80-300	Muddy with some sand

Based upon the sediment properties summarised in table 1 it is evident, for example, that the benthic A survey site has lower density sediment and smaller sediment particles than the other survey sites. It is likely that any seabed based scientific lander system may encounter significant sinking into the fine lower density sediment at the benthic A site than what may be encountered at the other benthic study sites. In contrast to this the benthic G survey site had higher density seabed based sediment with the largest particle size of all the survey sites. As such this was likely to offer a firmer foundation than the other survey sites, particularly benthic A, for a seabed based scientific instrumentation lander system. This information was used to help to estimate what the likely deployment conditions for the miniSTABLE benthic lander described in this report would be. Information relating to the possibility of lander frame sinking in the seabed was used to devise a system of brackets and adjustments for sensitive measurement systems positioned below the lander frame. The general idea was to estimate and then try to compensate for sinking of the benthic lander frame that may occur during a deployment. This helped to maintain, for example, the fragile eddy correlation system sensors, that are used to measure underwater dissolved oxygen flux, at an optimal or desired height range above the seabed based sediment. Compensation for frame settling into the seabed after the initial deployment was essential to enable the required seabed to lower water column oxygen flux measurements to occur.

2. The miniSTABLE seabed based benthic survey instrumentation system

The key features of the miniSTABLE benthic lander system design and experimental setup are described in this section. The labelled diagram in fig. 2 shows the arrangement of the main lander frame components prior to a deployment from RRS Discovery during the DY030 research cruise in May 2015.

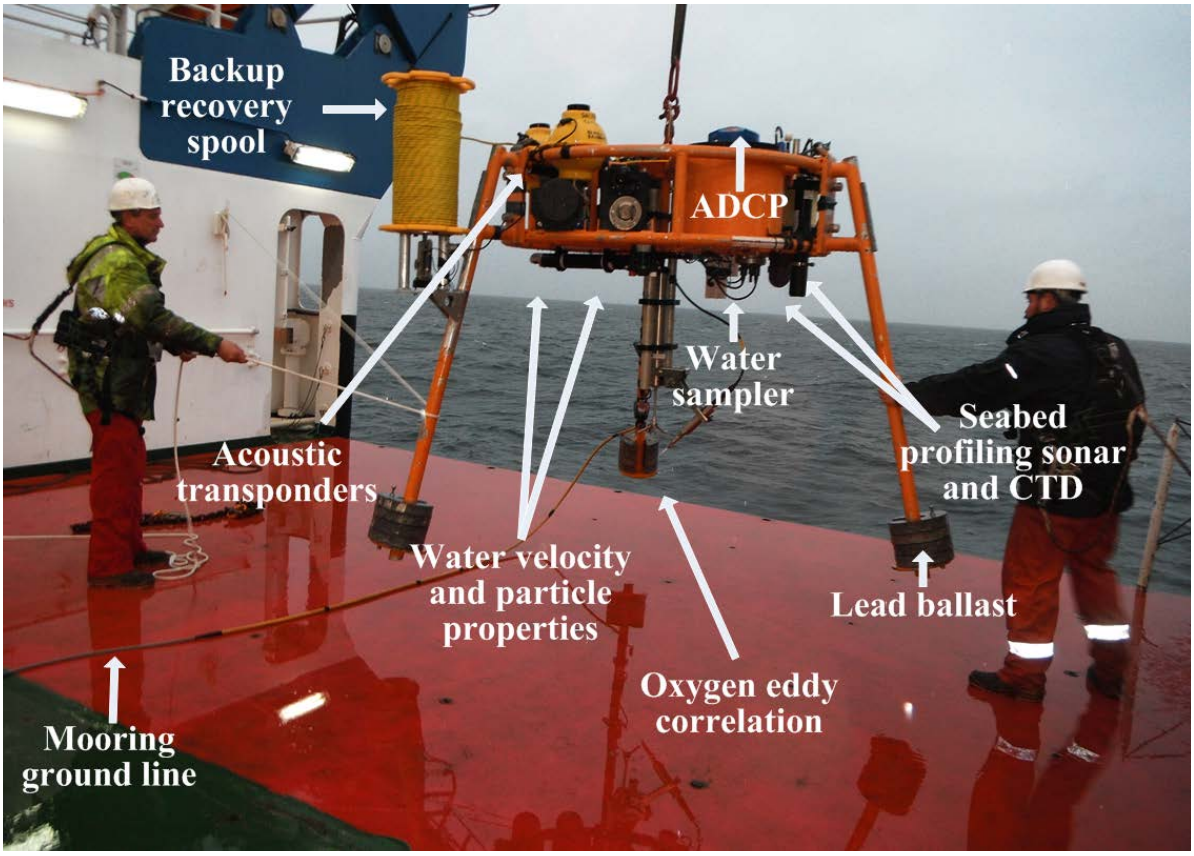


Fig. 2. The miniSTABLE benthic lander key components

The miniSTABLE lander is essentially an aluminium support frame with a tripod arrangement. Ballast comprising of 100kg of lead was fitted to each leg of the frame. This design was implemented to encourage the deployment of the frame to occur in a vertical orientation. Aluminium, lead and stainless steel fastenings were chosen as the base materials in order to discourage the establishment of residual magnetic fields within the apparatus. This prevents this potential source of interference from affecting sensitive scientific sensors such as electronic compasses that are commonly used by marine instrumentation as part of inbuilt attitude and heading sensors. A summary of the typical scientific sensor package used for the deployments of the miniSTABLE lander using RRS Discovery as part of the UK-SSB programme of research is listed in table 2.

Table. 2 – NOCL mini-STABLE benthic survey lander sensor overview

Sensor	Brief description
Sequoia LISST-100X	Laser in-situ transmissometry for sediment particle size.
Sequoia LISST-HOLO	Holographic sediment imaging camera.
Marine Electronics 3D ripple profiler	Seabed profiling sonar.
Satlantic SUNA	UV based optical nutrient sensor.
Teledyne Citadel NXIC CTD	CTD with a robust shielded inductive conductivity cell.
Nortek Aquadopp HR	High resolution downwards facing velocity meter.
1200KHz Teledyne RDI ADCP	Upward facing acoustic water current meter in a gimbal.
Aquatec Aquascat 1000R	Acoustic downwards facing sensor for sediment particle size and concentration measurements.
McLane RAS 100 water sampler	24 x 100ml water sample bags for timed water sampling and subsequent nutrient measurement. Included 24 suspended particulate matter (SPM) inline filters.
Unisense eddy correlation/oxygen flux sensing system	High speed dissolved oxygen micro-sensor, Aanderaa optode reference dissolved oxygen. Uses a Nortek Vector fast sampling acoustic water velocity meter.
Teledyne Benthos XT6001 (x 2)	Acoustic range finder and backup recovery system release. Two acoustic transponders were used to provide redundancy.

The suite of instrumentation used included sensors for suspended particulate measurement, acoustic systems for underwater current determination and sonar range finding for profiling the seabed directly below the lander frame. A CTD and a UV based dissolved nutrient sensor were included to assist with water quality measurements. In addition to this an automated water sampling system has been used for measuring dissolved inorganic nutrients and suspended particulate levels. A specialist eddy correlation system was used to provide high speed dissolved oxygen and water current measurements close to the seabed. This sensing system used a fragile, fast response dissolved oxygen micro-sensor and required specialised handling techniques. Two acoustic transponders were installed that could be used to provide underwater range information of the frame. The acoustic transponders could also be used to activate an underwater mechanical release system for the deployment of a backup recovery system for the lander frame. The layout, function and operation of the lander sensors, systems and the specialist operational procedures are discussed in more detail in the following sections of this document.

3. Seabed based scientific lander deployment and recovery

In terms of the deployment and recovery of the miniSTABLE lander frame, special handling procedures were required, particularly during the deployment of the frame due to the fragility of the eddy correlation dissolved oxygen sensor. A simplified diagram of the standard L shaped mooring arrangement that was used to deploy and recover the frame is shown in fig 3. The mooring comprised of a steel cable connecting a central lifting point on the frame to a seabed based anchor located some distance along the seabed, typically in the region of 150-200m, away from the lander. Between the seabed based cast steel anchor and the sea surface a surface expression in the form of a spherical buoy with a beacon was used. Buoyant rope, with a suitable amount of slack to compensate for tidal variations and allow the buoy to be lifted out of the water onto a recovery vessel, was used to connect the anchor weight to the surface buoy. This line maintained the surface buoy on station close to the anchor position on the seabed when the mooring was deployed. A separate smaller surface float and line were used as a mechanism to lift and access the coupling below the surface buoy to allow the mooring to be hauled on board a recovery vessel.

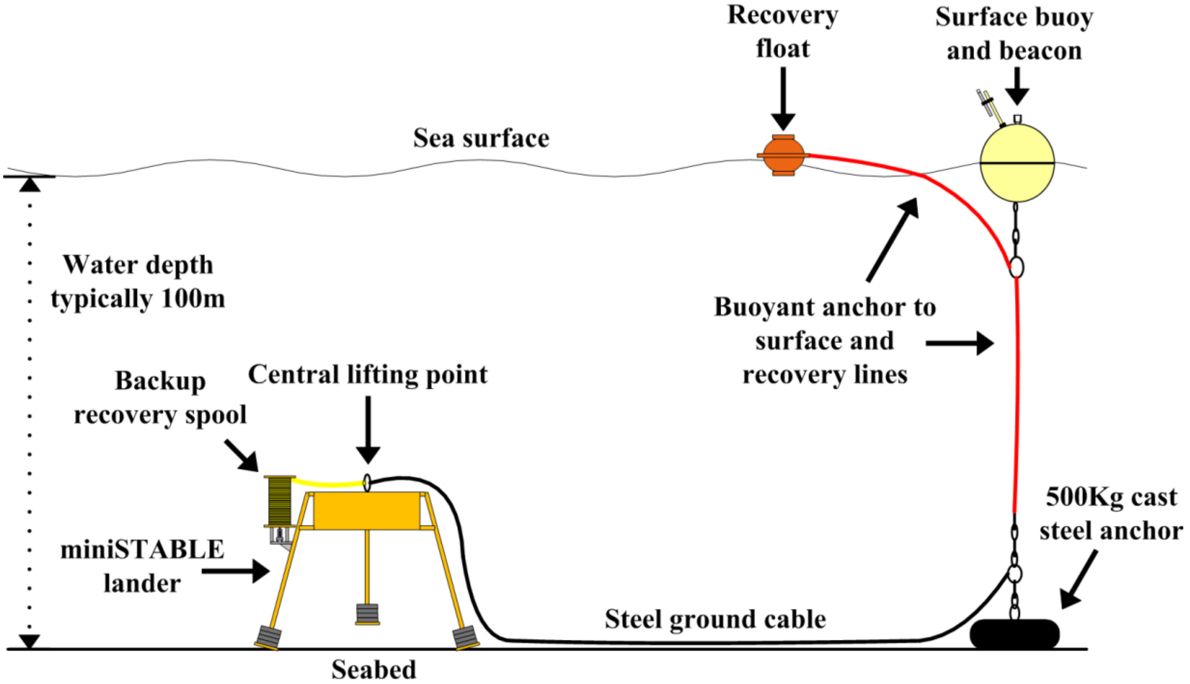


Fig. 3. Simplified mooring functional diagram

Deployment of the miniSTABLE lander involved lifting the frame over the stern of RRS Discovery using a block and crane with a vertical flexible line attached by an inline acoustic release. The frame was progressively lowered to the seabed using a central lifting point. A steel ground line was attached to an alternative frame central lifting or load point that was temporarily stowed during the deployment with breakable fastenings. Care was taken to maintain slack in the ground line during the lowering and deployment of the frame. After the lander frame had been carefully placed on the seabed the ship then slowly moved away from the frame to lay the ground line, taking care not to tension the line to avoid snatching or dragging of the deployed frame. After a suitable length of ground line had been laid on the seabed, the deployment of a cast anchor would then commence with the ship holding station during this process. After the cast anchor was placed on the seabed the remainder of the buoyant surface to anchor line would be carefully paid out from the stern of RRS Discovery until most of the line had been deployed. The process would be completed by deploying the surface buoy and recovery line plus float as the ship slowly moved away from the mooring location.

Recovery of the mooring would essentially be the reverse of the deployment procedure. The recovery float was snagged first and then hauled on-board. A deck winch, a crane and a wide sheave block over the stern of the ship were then used to vertically haul the surface buoy. This allowed access to the mooring line couplings on the underside of the buoy.

Following this the cast anchor would then be lifted on board using the buoyant line connection. This subsequently allowed access the steel ground line to cast anchor mooring coupling. The recovery process would then proceed with the ground line being de-coupled and winched on board with the ship progressively moving closer to the miniSTABLE lander frame deployment location. The process would then be completed by the crane and wide sheave block being used to first vertically raise the lander frame from the seabed, out of the water, and then move it onto the stern of the ship.

The deployment and recovery of the frame are complex sequences of operations involving a series of different mooring components such as lines, cables, metallic links and shackles. Although moorings tend to be robust, it is possible for moorings to fail for a number of reasons such as inadvertent tensioning beyond design limits and failure of mechanical couplings. An alternative method for recovering the frame was designed and implemented in the form of a small buoy with a coil of high strength, neutrally buoyant line that was also attached one of the lander frame central lifting points. A mechanical release was used to hold the backup recovery buoy in position on a mounting on the side of the lander frame. Should the mooring fail then a deck unit and over the side acoustic transducer plus cable can be lowered into the near surface seawater from a recovery vessel to communicate with the two XT6001 acoustic transponders mounted on the upper section of the lander frame. A burn wire based release mechanism connected to the XT6001 units can then be activated. Two acoustic transponders have been included to provide redundancy should one of the XT6001 transponders fail. When the burn wire based release has been activated the backup buoy with a spool of line attached should deploy. As the buoy heads towards the sea surface due to its buoyancy the line around the buoy should slowly uncoil. When the buoy surfaces the buoy or line can be snagged and hauled on-board to access the high strength line attached to the central lifting point on the frame. The potential for the buoy to entangle or snag due to problems with the line, release mechanism and entanglement with the mooring are possible reasons for the failure of the recovery buoy of this type to operate correctly. Therefore the line spooling buoy was used only as a secondary recovery mechanism should the typically more reliable and more robust main L shaped mooring arrangement fail.

Care must be taken not to disturb or damage the fragile eddy correlation fast sampling dissolved oxygen sensor and the sensitive Nortek Vector water velocity meter. These sensing systems are mounted below the main upper section of the lander frame, as shown in the labelled photograph in fig. 4. The dissolved oxygen sensor and vector water current meter need to be mounted in a position below the frame away from disturbances from surrounding sensors, cables and the host frame. The arrangement as shown in fig. 4 is vulnerable to damage, particularly during the frame deployment. Any mechanical shock or vibration can potentially damage or degrade the performance of the delicate glass envelope based dissolved oxygen micro-sensor used by the eddy correlation system. An adjustable bracket system was used to mount the oxygen micro-sensor and the associated signal amplifier unit from the body of the Nortek Vector water velocity sensor. The oxygen micro-sensor was angled to move the signal amplifier unit and the associated electrical connection cable away from the sensor tip and the vector transducer array to prevent disturbance of the sensitive measurements. The tip of the dissolved oxygen sensor was aligned to a position below the Nortek vector close to a small sampling area or volume that the vector analyses to determine the underwater velocity when the frame was deployed. This velocity sampling volume was normally at a distance of 15cm below the central flat transducer surface within the vector acoustic sensing array. A normal distance above the seabed for the velocity determination position for the vector and the corresponding position for the end of the fine tip on the dissolved oxygen sensor would be 10-50cm.

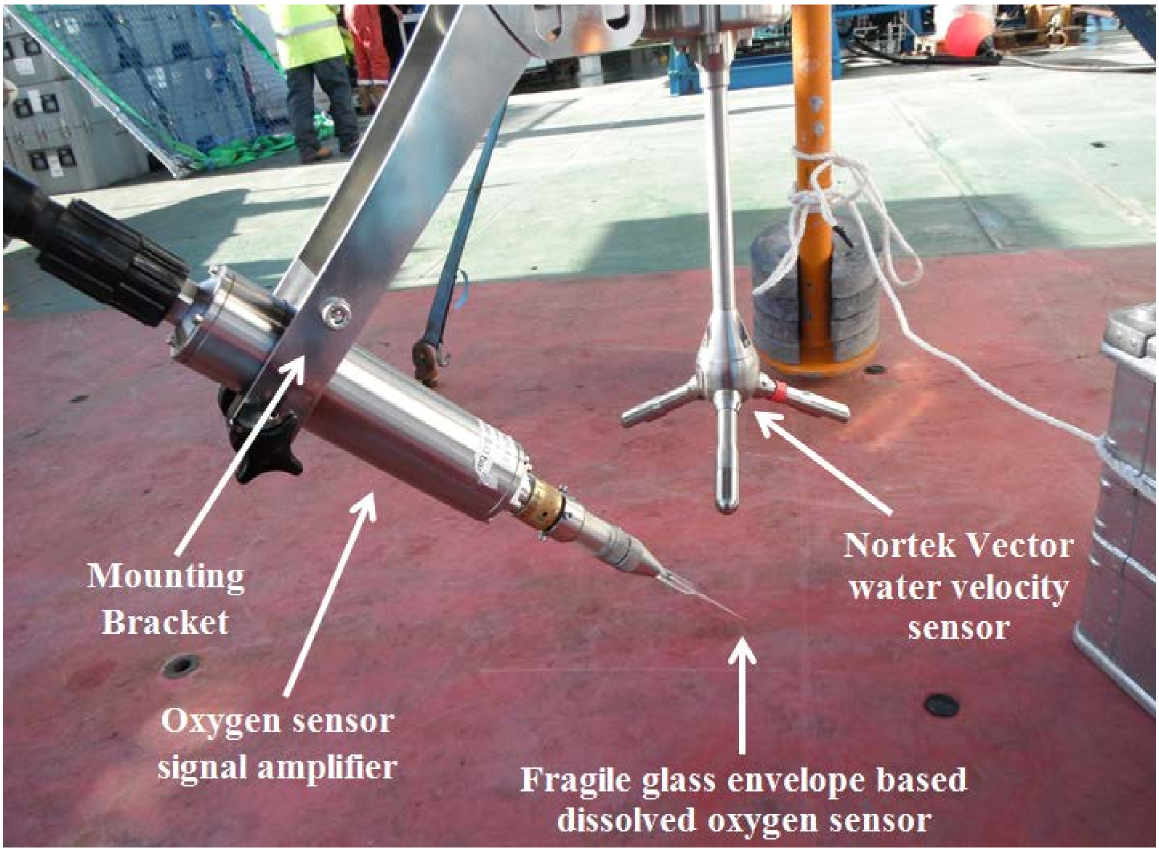


Fig. 4. The eddy correlation sensing arrangement

A labelled photograph of the acoustic release and lifting strop arrangement that was used to carefully and progressively deploy the lander frame is shown in fig. 5. An inline acoustic release lifted by a crane had a flexible lifting strop looped through one of the miniSTABLE central lifting points. The frame was slowly lowered to the seabed with a line attached to the upper part of the acoustic release via a block suspended from a crane. A ship based deck unit and over the side acoustic transducer were used to monitor the depth of the acoustic inline release. As the lander frame approached the seabed the rate of descent was slowed. The tension in this line was monitored manually until the frame was deemed to be on the seabed. Slack was also maintained with the ground line as it was lowered in tandem with the frame to prevent any disturbance to the frame descent. At this stage the acoustic release was activated and then the release was raised, slowly at first, to carefully clear the lifting strop away from the lander frame central lifting point without disturbing the frame position. A prerequisite to this process was a calm sea state to avoid excessive ship motion, surface waves or a hard landing on the seabed risking damage to the fragile oxygen sensor. The mooring ground cable was attached to a second frame lifting point and then the ground cable was carefully routed along one of the frame legs. The mooring line was held and stowed in position on the frame using temporary breakable plastic fasteners and adhesive tape. The general requirements were to carefully route and control the ground line position along the lander frame. The aim of the ground line temporary fastening to the lander frame was to also discourage any slack in the ground line from approaching the fragile eddy correlation sensors or accumulating underneath the frame. This was necessary to avoid possible disturbance or damage to the sensitive measurement systems used by the lander. When the frame was recovered the plastic fasteners progressively broke as the ground line was tensioned to allow the frame to be lifted vertically.

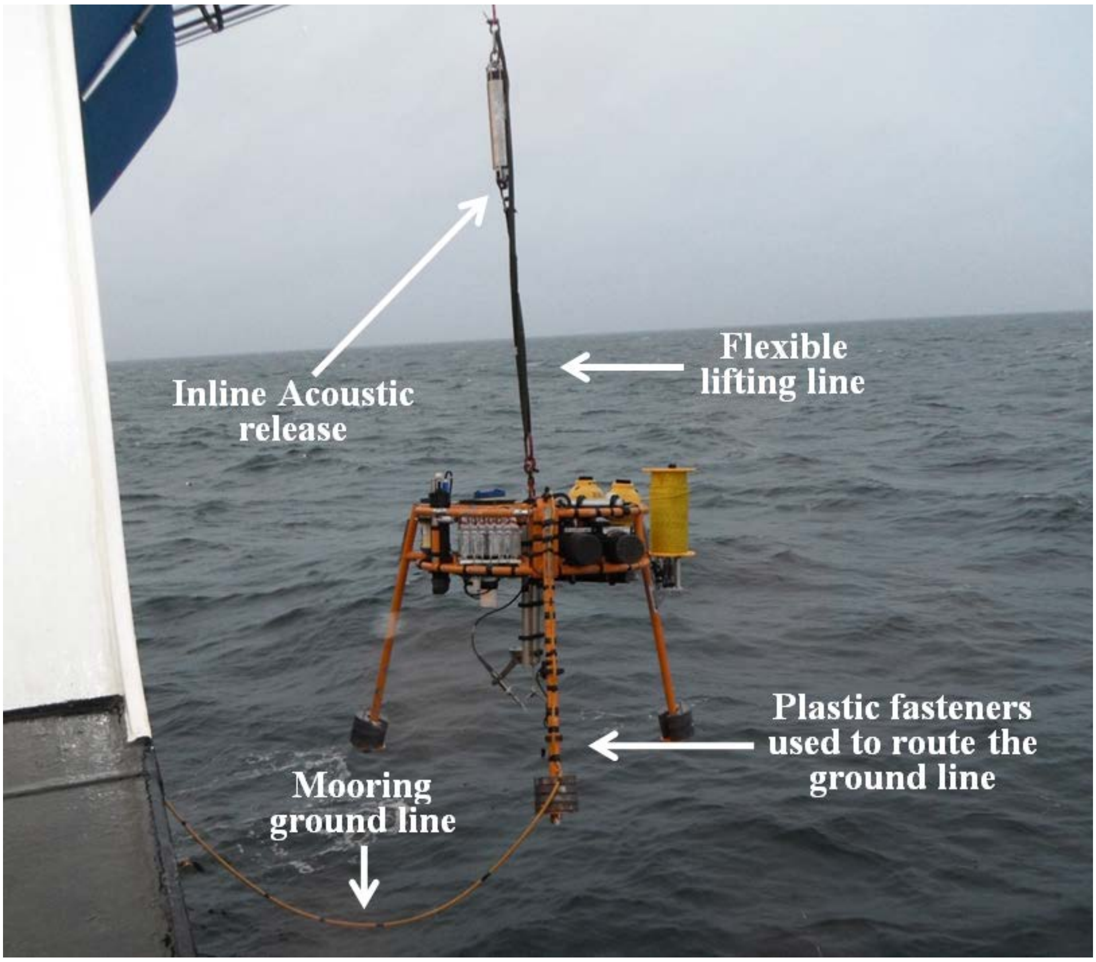


Fig. 5. miniSTABLE frame deployment from RRS Discovery

The first four metres of the ground line from the frame lifting point were insulated using a plastic sleeve. This was to prevent the possibility of the onset of galvanic corrosion if the steel ground line was to come into contact with the aluminium frame. Additional details relating to the mooring design and the sequences of deployment and recovery operations are included in appendix B of this document.

4. Sensing Systems and Scientific Data

This section provides a more detailed review of the operation of each lander sensor and instrumentation system in the configuration selected for the UK-SSB project benthic surveys. The lander instruments were typically housed in individual pressure cases. Scientific data was recorded inside each instrument and either an internal or an external battery based power source was used. The scientific data sets generated during a lander deployment were collected after the lander frame recovery. To aid the description of the operation of the scientific sensors in this section a series of measurement data plots have been used. These plots are for illustrative purposes and represent the raw or preliminary output from a particular instrument after it was recovered.

Following the completion of the benthic lander deployments described in this document an extensive programme of work will be undertaken to quality check the instrumentation data using a series of techniques. These include validation by external sensors such as the use of RRS Discovery based CTD carousel. This was used for comparative measurements and water column measurement profiles that were recorded in close proximity to the deployed lander during the survey cruises. Laboratory based sensor checks in controlled conditions before and after a deployment was another technique used to monitor and control the sensor data quality. These methods will subsequently be used to assess the raw scientific data quality to ensure that the measurements from the sensors used are correctly calibrated. Any suspect or lower quality data can be highlighted during this process and if necessary excluded from the final quality controlled data output. Appropriate corrections will be applied as and when required to calibrate scientific measurement data produced from this research work. This data output will form an important component of the evolving data processing and analysis process for the UK-SSB research programme. The aim or primary goal of this work will be to derive quality controlled scientific measurements. In line with standard marine data management best practices, this information will be traceable back to the raw or native format collected from the instruments after they were recovered from a deployment.

4.1 The LISST-100X

The basic layout of the LISST-100X particle size and distribution sensing system is shown in fig. 6. This type of sensor is used for determining particle sizes that are present in the water column. A parallel or collimated laser beam passes through a sampling volume on the instrument that is typically 50mm long before being registered by a detector. The detector measures ranges of angular scattering of the laser beam that may occur by particles in the sampling volume. The instrument includes sensors for underwater temperature and depth.

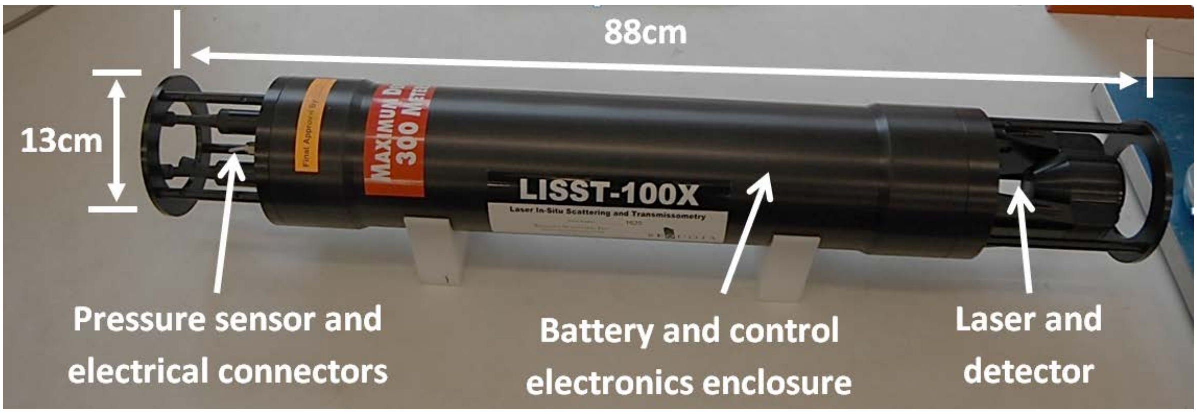


Fig. 6. The Sequoia LISST-100X laser in-situ transmissometry

The placement of the instrument on the lander frame was intended to ensure that the sample volume is subjected to particle sizes and concentrations that are representative of the local conditions close to the seabed when the lander was deployed. The exploitation of a specialised ring detector, and mathematical data processing, allows measurements of the suspended particle size and the particle size distribution within the instrument detection volume. Careful attention must be paid to ensuring that the laser and associated optics for the detector are correctly aligned and free from contamination. The LISST-100X instrument also included an inbuilt temperature and depth measurement capability. Processing of the data generated by the instrument is illustrated by the example plot in fig. 7, which is based upon measurements during the DY030 research cruise. During the deployments of the NOCL lander the LISST-100X instrument was used to provide measurements of the suspended sediment particle size and distribution. This helped to generate information relating to the general suspended sediment consistency and variation close to the seabed in the key scientific survey areas during the lander deployments.

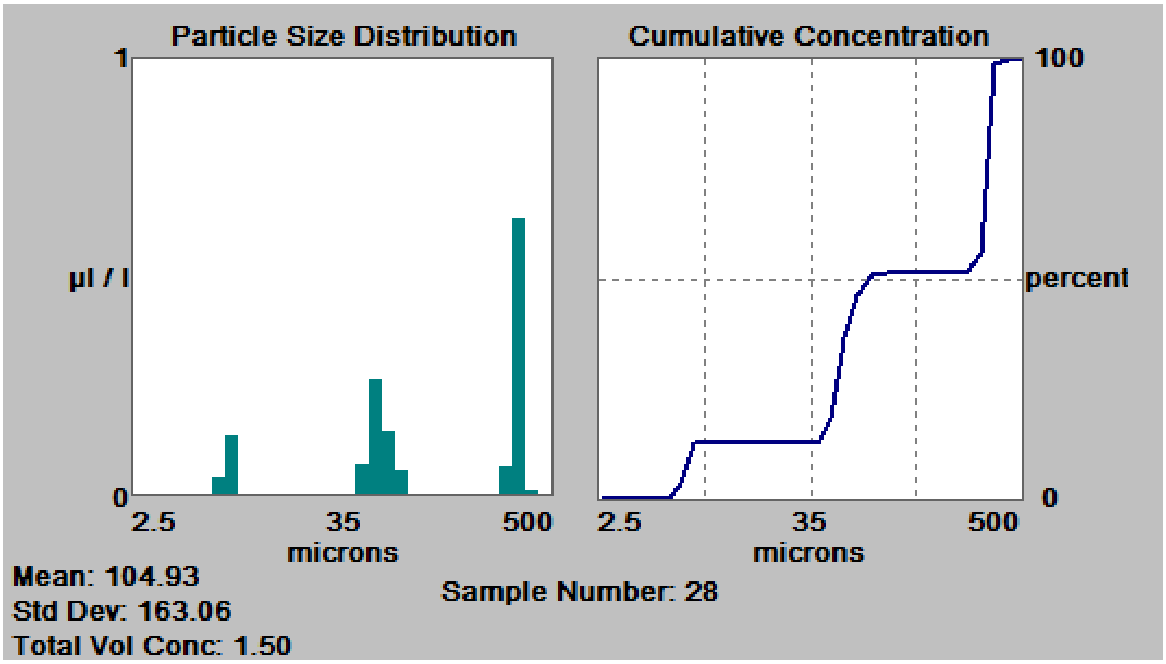


Fig. 7. LISST-100X particle size distribution plot using the manufacturers software

4.2 LISST-HOLO

A labelled photograph of the LISST-HOLO is shown in fig. 8. This sensor uses laser scattering and a camera based detector to generate a series of images, typically at 1mm intervals, along a sample volume of up to 50mm in length. Images can be captured at variable position increments along the sample volume. This information can be used to build up a holographic sequence of pictorial representations of particles in the sample volume that are in focus at that particular range.

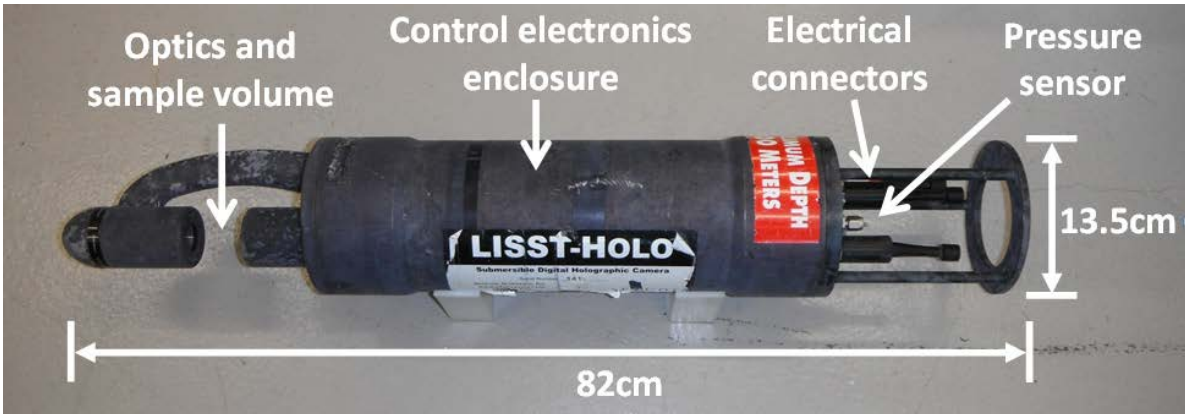


Fig. 8. The Sequoia LISST-HOLO holographic particle size analyser

Particle sizes can be determined and the ability to take a sequence of images at different positions along the sample volume can be used to determine the particle concentration. An example raw and processed image is shown in fig. 9, whereby an area of interest of a composite raw image to the left, defined by the square with a highlighted perimeter, has been processed.

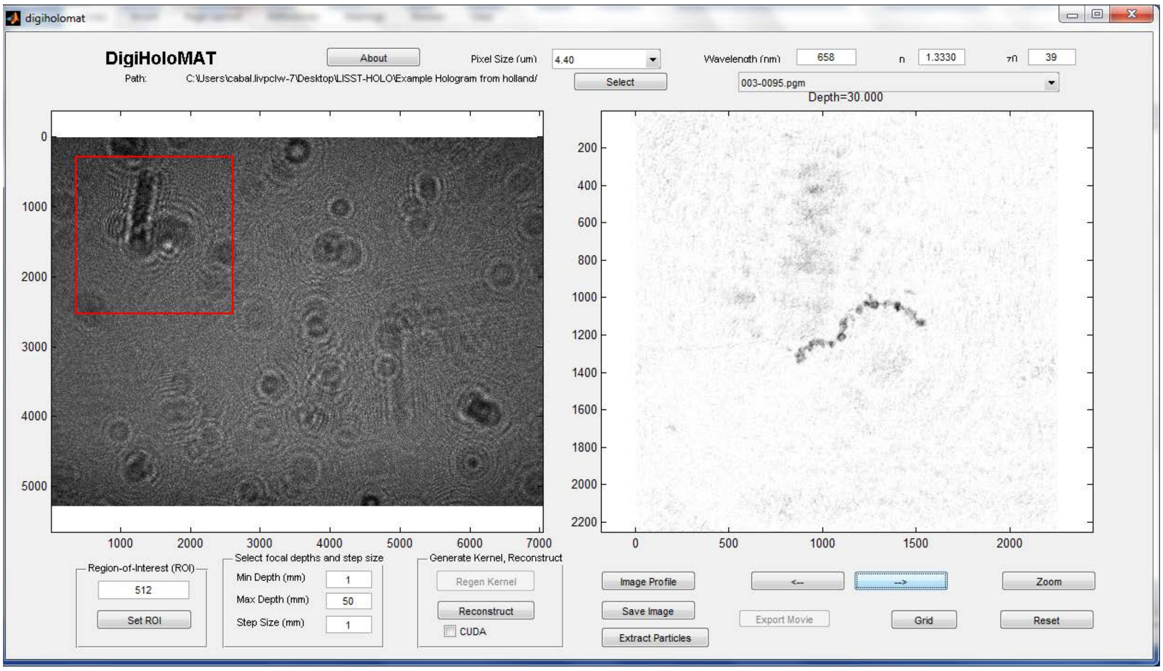


Fig. 9. RRS Discovery DY030 research cruise LISST-HOLO raw composite image and region of interest image slice at a depth of 30mm into the sample volume. The scale is in µm.

Processing of the highlighted part of the raw image to the left of fig. 9 produced the calibrated image slice to the right of the figure. The calibrated image slice shows the features of a larger particle at a 30mm position along the detecting volume. This detailed or zoomed image slice has dimensions of 2200µm x 2200µm (2.2mm x 2.2mm). Computer based image processing of the slices of the composite or raw image from the LISST-HOLO can be used to determine the size, features and concentration of particulate matter in the detecting volume of the instrument. The LISST-HOLO was positioned approximately 2m above the seabed for the benthic lander deployments described in this document, with the intention of studying near seabed suspended particulate matter features. A temperature and depth measuring capability was included with the instrument.

4.3 The 3D Ripple Profiler

This 3D ripple profiler illustrated in fig. 10 is essentially a self-recording instrument that mechanically scans in a horizontal plane a sonar range finder with a narrow cone shaped beam. After each scan a small angular change is made using a mechanical scanning arrangement to build up a sequence of range information of the seabed below the scanning system. This can be used to construct a pictorial representation of the seabed in terms of the range from the sonar scanning system used by the profiler. Features in the seabed below the sonar such as sand ripples or changes to the seabed profile due to factors such as sediment transport can be highlighted and tracked by this sensor. The instrument is normally mounted vertically below or to the side of the lander frame with the acoustic transducer cover pointing downwards. The 3D ripple profiler system also includes seawater conductivity, seawater temperature and attitude sensors. The attitude sensors can be used to monitor the orientation of the lander frame during a deployment.

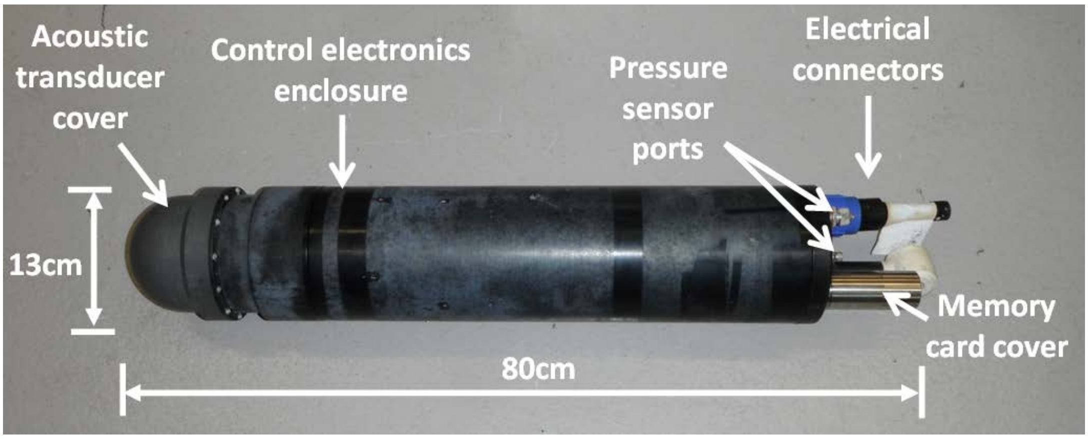


Fig. 10. The 3D Sand Ripple Profiling and Logging Sonar

An example processed data plot indicating the seabed distance and terrain below the lander frame, for a portion of the deployment at the benthic G survey site during DY034, is shown in fig.11. The area below the NOCL lander frame at a range of approximately 1.5m is indicated by the circular surface plot. The interference caused by the lander frame legs can be seen in the surface plot, with the range of the acoustic scanning appearing to be extending beyond the area directly underneath the lander frame. Interference generated by the eddy correlation sensors mounted below the frame was evident, as indicated in fig. 11.

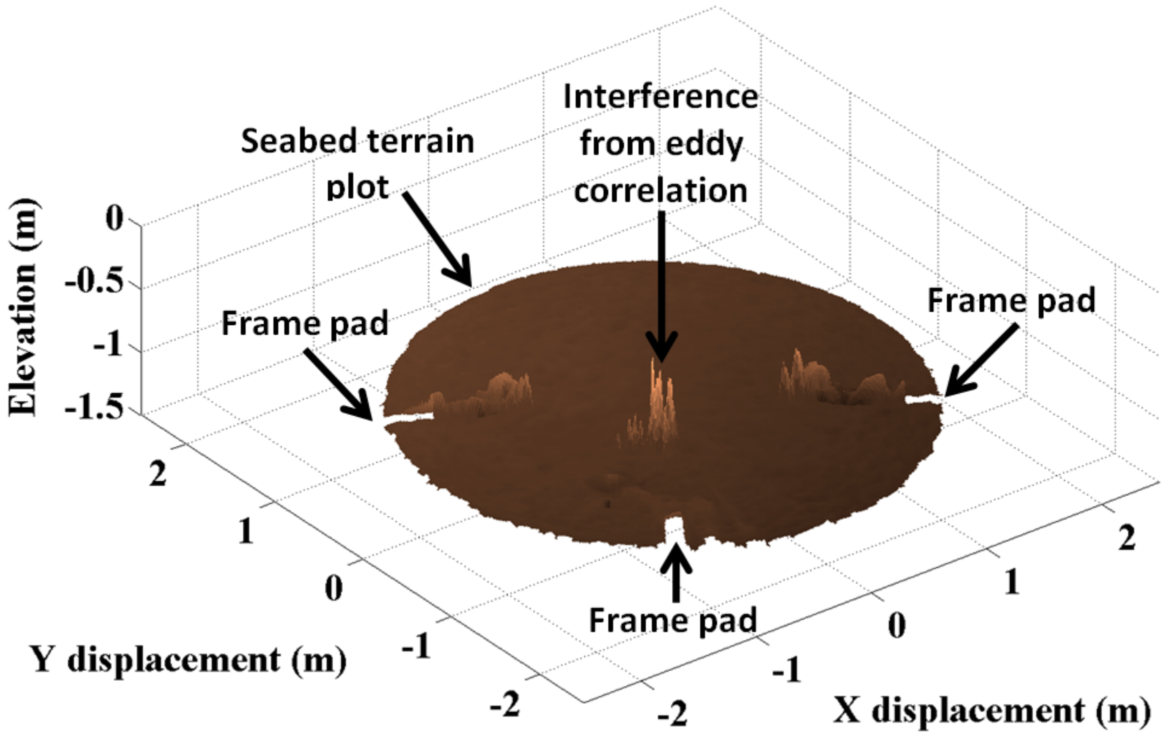


Fig. 11. Preliminary plot of the seabed terrain using the 3D ripple profiling sonar

This sonar range information or ‘image’ from the 3D ripple profiler seems to indicate the terrain below the lander frame at the benthic G survey site was relatively flat with only the occasional seabed based feature such as minor undulations.

4.4 Satlantic SUNA Optical Nutrient Sensor

The Satlantic Submersible Ultraviolet Nitrate Analyzer (SUNA), as shown in the labelled picture in fig. 12, is a water quality monitoring sensor that uses ultraviolet absorption spectroscopy. A sample analysis volume or chamber is located approximately a third of the way along the instrument. The sensor is capable of delivering an output of real time and continuous dissolved nitrate level measurements. A copper anti-biofouling guard was used for the deployments of this sensor as part of the UK-SSB cruise programme. The sample volume was facing downward to discourage the accumulation of sediment fouling in the sensor optics and the sensor was mounted below the upper part of the lander frame. The instrument typically requires a warm up period of 8-10 minutes after it has been powered before a mooring based stable measurement will be generated. When correctly warmed up and stabilised the update rate from the instrument is one measurement every 2 seconds.

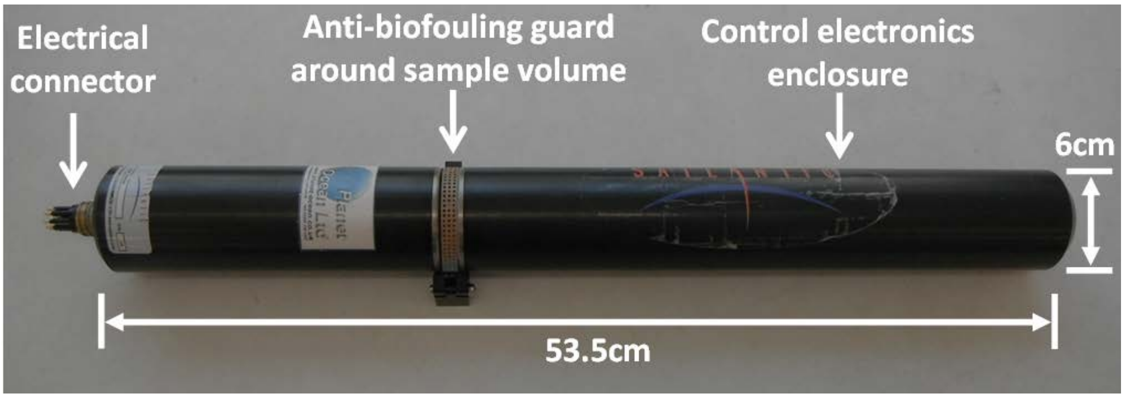


Fig. 12. The Satlantic SUNA optical nutrient sensor

An example raw data output plot from the SUNA of dissolved nitrate measurements from the instrument in units of µM (micro Molar) is shown in in fig. 13. These measurements are from a 2 day deployment of the sensor at the benthic G survey area from 8th to 10th August 2015 as part of the DY034 research cruise.

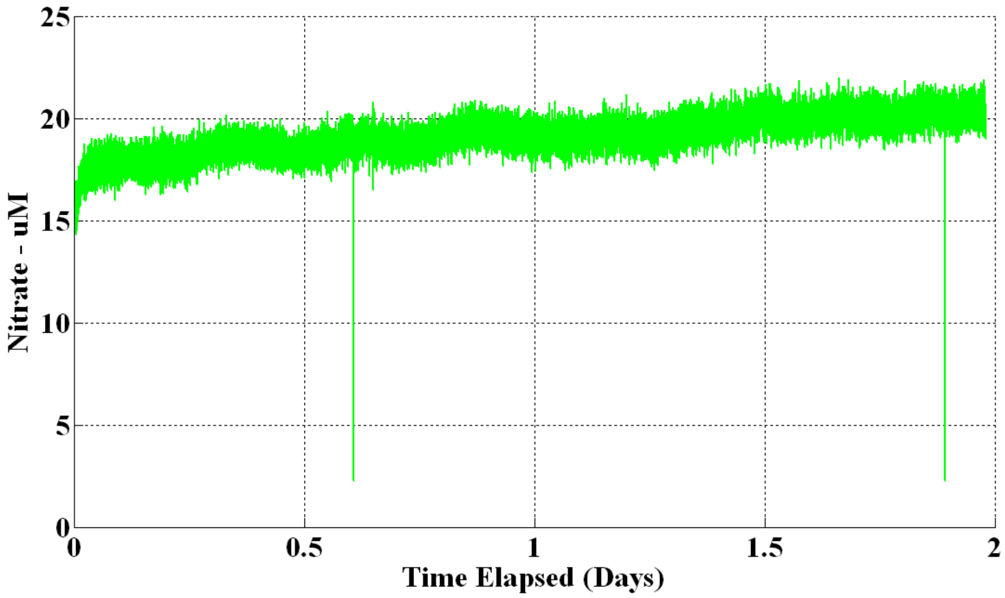


Fig. 13. Example Plot of Satlantic SUNA measured output

The data plot in fig. 13 shows measurements between approximately 16 µM and 21µM during the deployment with a higher frequency variance or fluctuation envelope of approximately 3µM. There is some evidence of spiking or interference in the raw measurements generated, as shown in the plot. The general long term trend of measurements over the 2 day deployment indicates a nitrate concentration increase from approximately 16µM to 21µM during the deployment.

4.5 Teledyne Citadel NXIC CTD

The Teledyne Citadel seawater conductivity, temperature and depth sensor (CTD) is based around a Non eXternal Inductive Conductivity (NXIC) measurement cell. A photograph with the basic layout of the CTD indicated is shown in fig. 14.

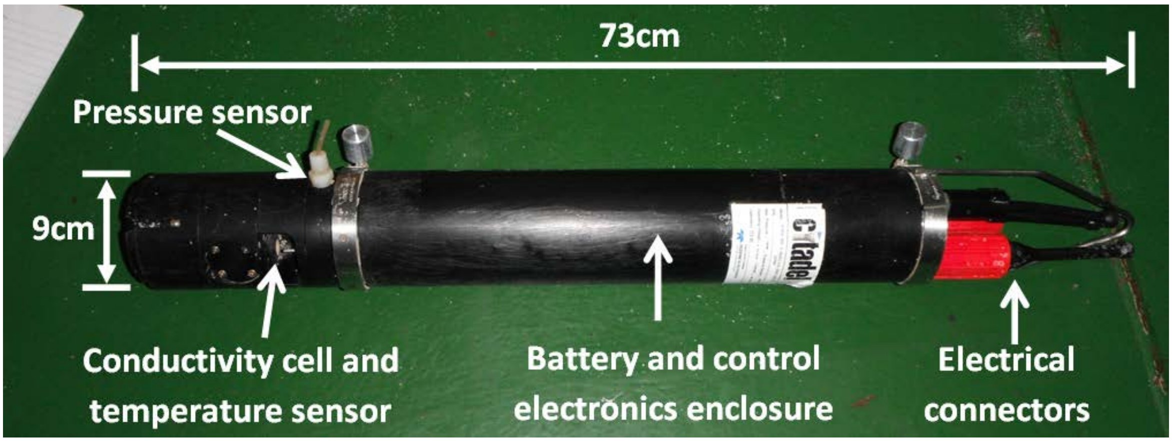


Fig. 14. The Teledyne Citadel NXIC self-recording CTD

This type of CTD tends to provide robust measurements including derived salinity in benthic survey environments. In particular the seawater conductivity measurement cell, from which the salinity can be derived, tends to be resistant to influence by sediment and biofouling. In addition to this the cleaning of the conductivity cell between deployments is relatively straightforward with a lint free cloth, tap water and a mild detergent commonly being used. A sequence of raw data plots from the CTD for a 2 day deployment at the benthic G survey site during the DY034 research cruise are shown in figs 15-17. Small variations in the relatively stable derived near seabed salinity of approximately 35.24 PSU can be seen in the derived salinity plot in fig. 15.

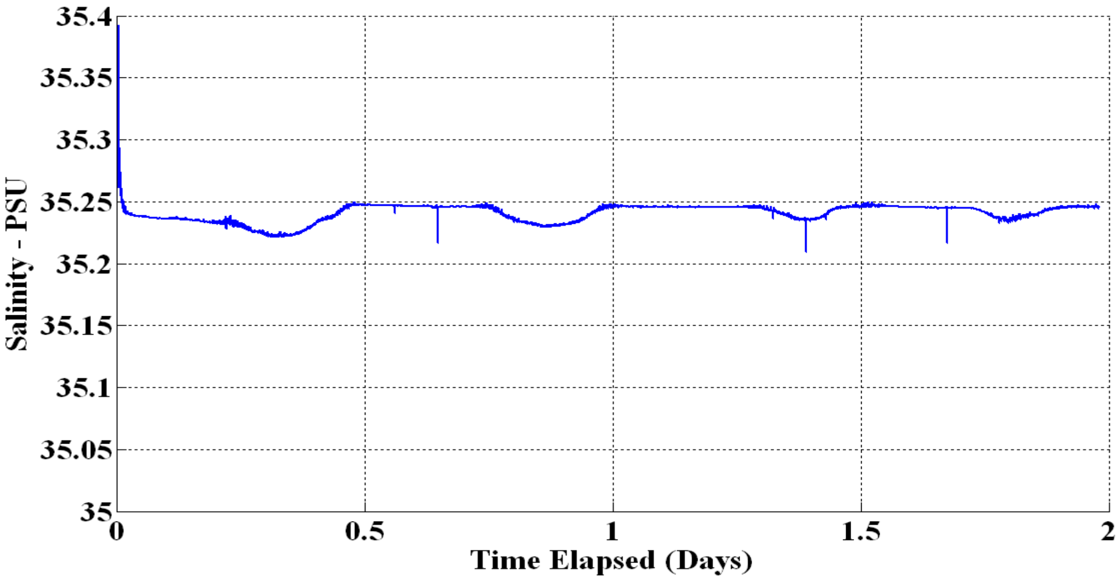


Fig. 15. CTD derived salinity plot for the DY034 benthic G survey site deployment

Similar variations in sync with the derived salinity can be seen in the near seabed temperature around a nominal 9.8°C in the plot in fig. 16. The pressure record from the Teledyne Citadel NXIC CTD is shown in fig. 17. Changes in the water depth and thus the pressure record can be seen clearly in this plot in response to tidal cycles over the two day deployment of the CTD.

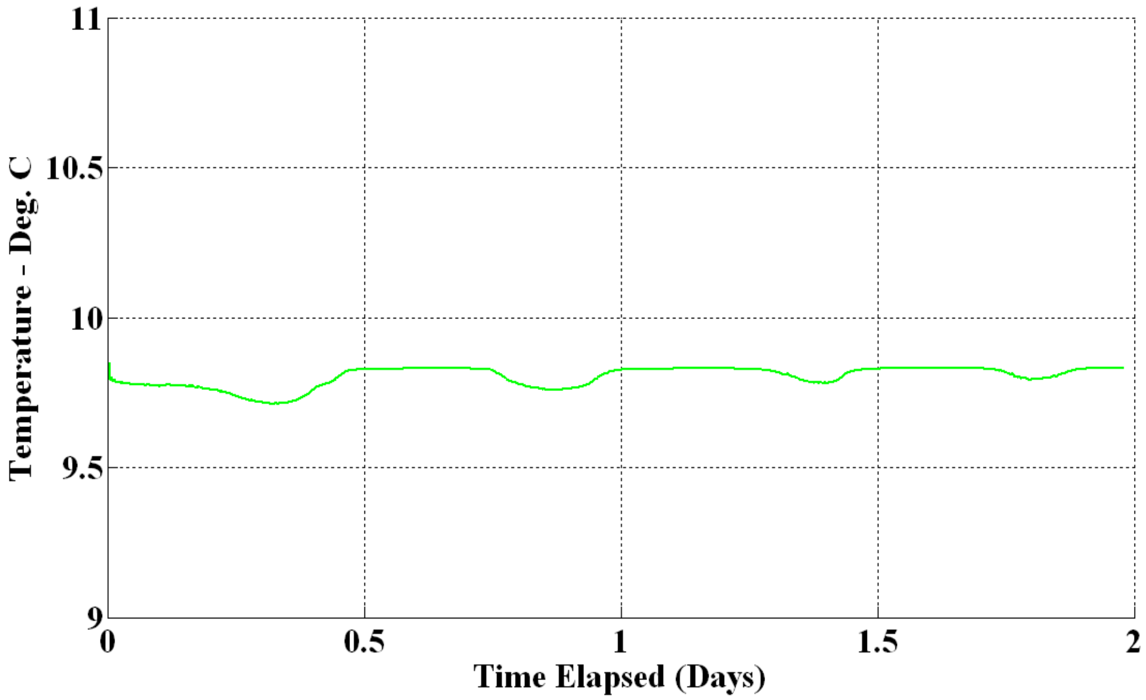


Fig. 16. CTD measured temperature plot for the DY034 benthic G survey site deployment

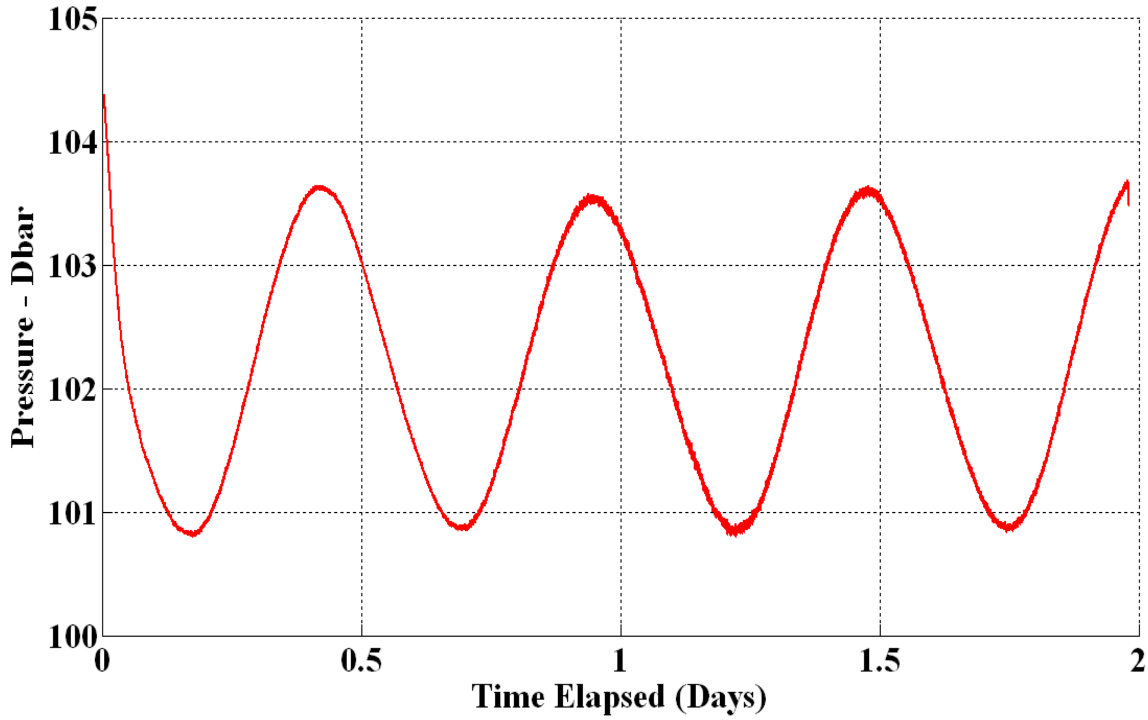


Fig. 17. CTD measured pressure for the DY034 benthic G survey site deployment

4.6 Nortek Aquadopp HR water velocity sensor

The Nortek Aquadopp HR, as shown in the labelled photograph in fig. 18, was used as a water current sensor with the acoustic sensor array facing downwards. The Aquadopp was located below the main circular upper section of the NOCL benthic lander frame. In the downward configuration the instrument is capable of producing velocity measurements that comprise of horizontal and vertical components of the water velocity below the acoustic sensor array. The basic principle of operation is that a water velocity measurement is achieved by examining the phase shift in the signal echoes to the transducer array from two or more consecutive acoustic pulses. For the deployments for the UK-SSB programme, the Aquadopp was configured to record water velocity measurements at 10cm intervals or bin sizes, from a starting position of 0.2m below the acoustic sensor array to a distance of up to 1.7m below the lander frame. The Aquadopp was typically located at a range of less than 1.7m from the seabed. The general intention was to generate a velocity profile at 10cm intervals from a position close to the sensor array of the instrument to the seabed below the Aquadopp. At higher distances or bin numbers from the acoustic sensor array the seabed would tend to generate interference with the velocity measurements. In addition to this high sediment concentrations close to the seabed could also interfere with acoustically derived water velocity measurements. Careful interpretation of the velocity measurements from the instrument is therefore required to exclude measurements where signal contamination or interference may have occurred. The Aquadopp included water temperature and pressure sensors, an internal electronic compass for heading measurement and pitch plus roll sensors. This inbuilt measurement of the orientation of the Aquadopp allows the attitude of the host NOCL miniSTABLE lander frame, to which the instrument was attached, to be monitored during a deployment.

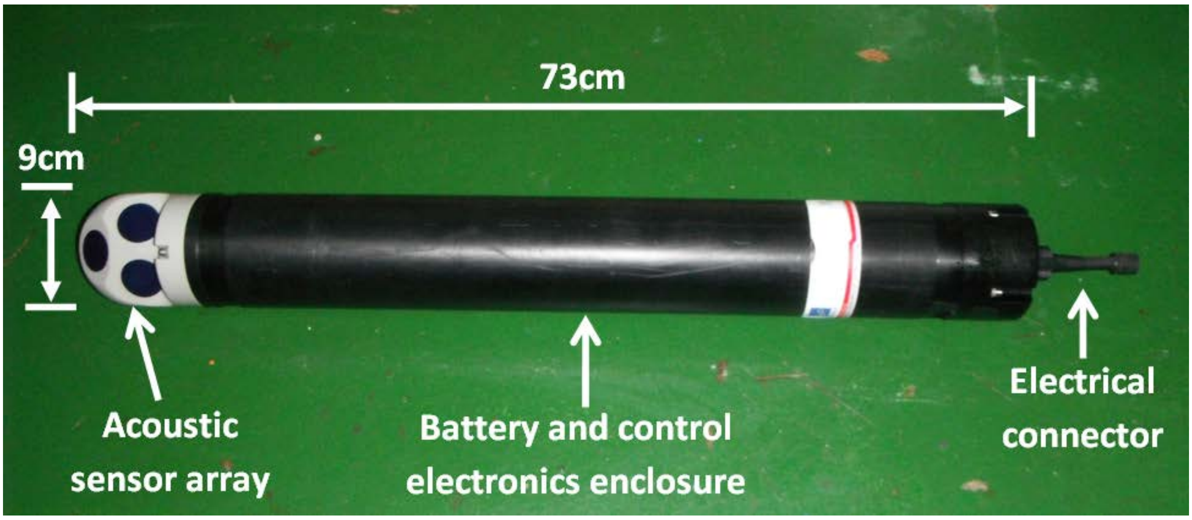


Fig. 18. The Nortek Aquadopp HR was used as a downward facing water velocity sensor

The data plots in fig. 19, from a lander deployment at the benthic A survey site during the DY034 research cruise, show graphs of the variations in the upward water velocities measured by the Aquadopp. The sample bins plotted are at distances of 0.2m, 0.3m and 0.4m below the acoustic sensor array. The plots in fig. 19 represent a 60 second segment of the raw vertical velocity measurements from the Aquadopp relative to its sensor array. For this deployment the instrument was configured to sample the water velocity at a frequency of eight measurements per second (8Hz).

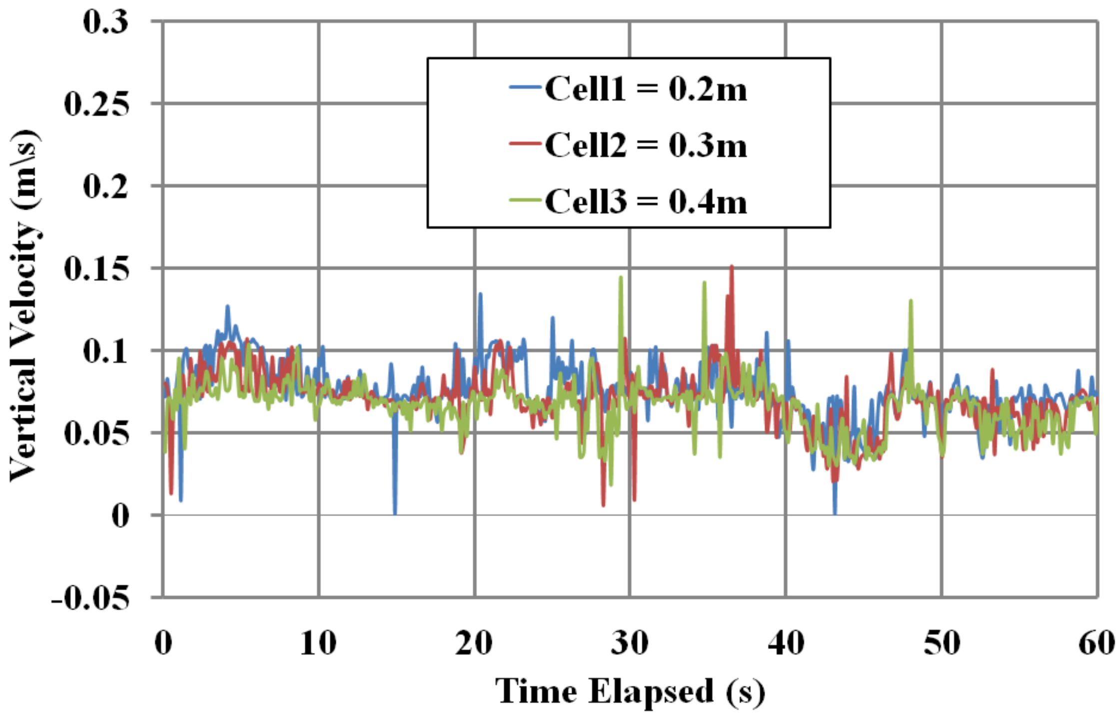


Fig. 19. Plot of velocity profiles from the Aquadopp HR from a deployment at the benthic A survey site during the DY34 research cruise

While there is some evidence of spiking and noise in the raw measurements of water velocity shown in fig.19, the general trend can clearly be seen. Interference from, for example, large particles or obstructions in the water column below the acoustic sensor array can affect the quality of the water velocity measurement produced. As shown by the graphs in fig. 19 the vertical components of the underwater velocity at 0.2m, 0.3m and 0.4m below the Aquadopp transducers was measured to be varying between approximately 0.05 and 0.1m\s. These raw data shown graphically in fig. 19 would typically be processed to remove poorer quality measurements to form a final quality controlled data set. Techniques including the interrogation of the various measurement quality indicators from the Aquadopp such as the returned acoustic signal strength, signal filtering and the measurement signal quality or correlation would typically be used. This allows the water velocity measurements produced by the Aquadop with a high degree of quality or certainty to be identified and included in a quality controlled version of the water velocity measurement data set.

4.7 The Aquatec Aquascat 1000r

This is an instrument that uses four downward facing acoustic transducers to measure the strength of high frequency acoustic signals reflected by particulate in the water below the sensor array. From the strength and characteristics of the reflected acoustic signals it is possible to deduce information relating to the size and concentration of particles suspended in the water column. It is common to process the acoustic information from the sensors at a series of discrete distances or 'bins' between the acoustic transducer array and the seabed. This allows profiles of suspended particle size and concentrations to be derived that comprise of a series of point measurements at regular intervals below the acoustic transducers. A typical range between the acoustic transducers and the seabed would be 1.5-2m, with a 10mm measurement interval or bin size normally being used. The Aquascat 1000r system also includes seawater pressure and seawater temperature measurement sensors. Photographs of the Aquascat 1000r and the transducer array are shown in figs 20 and 21.

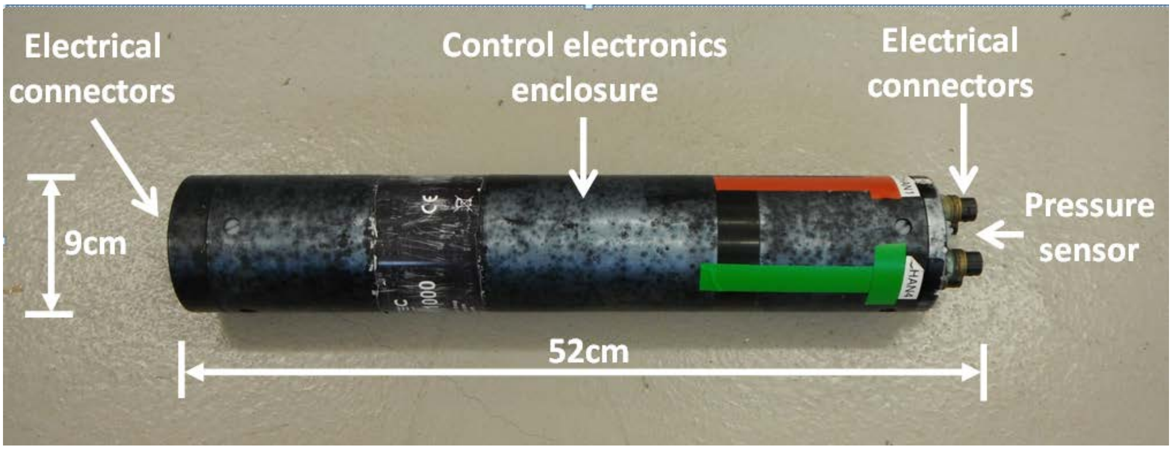


Fig. 20. Basic layout of the Aquatec Aquascat 1000r

For a deployment the flat section on the end of each of the four acoustic transducers connected to the Aquascat points downwards on the underside of the lander frame, as shown in fig. 21. The general scale of the mounting for the transducers is also shown in the photograph of the arrangement that was used. Care needs to be taken before a deployment to ensure that the transducer mounting bracket was configured so that the sensing face of each transducer is at the same height and pointing vertically downwards.

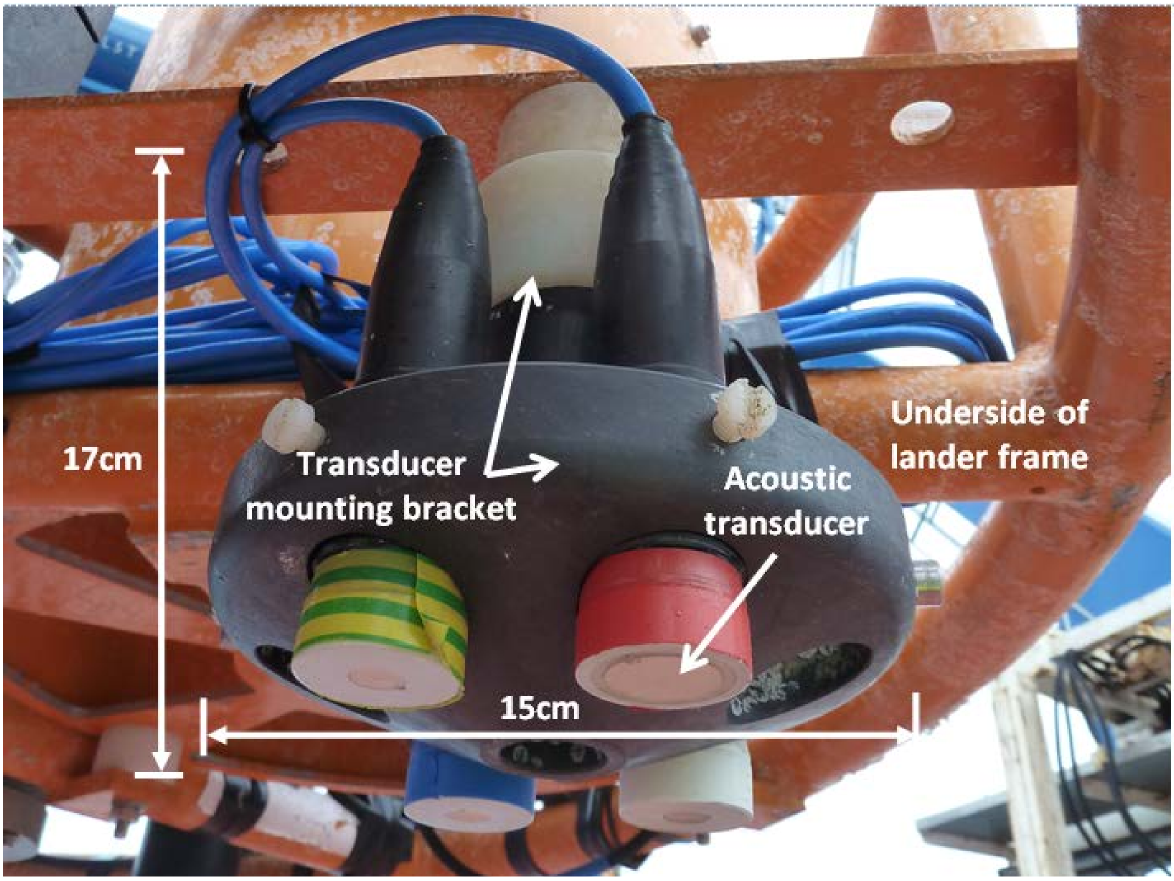


Fig. 21. Close up picture of Aquascat 1, 2, 3 and 4 MHz transducers and mounting

An example data plot from one hour of recorded data by the 3MHz channel of the Aquascat during a DY034 deployment at the benthic H survey site is shown in fig. 22. A clear and strong reflected signal at 110cm from the transducer can be seen, as indicated by the horizontal red line. This indicates the position of the seabed below the sensor array.

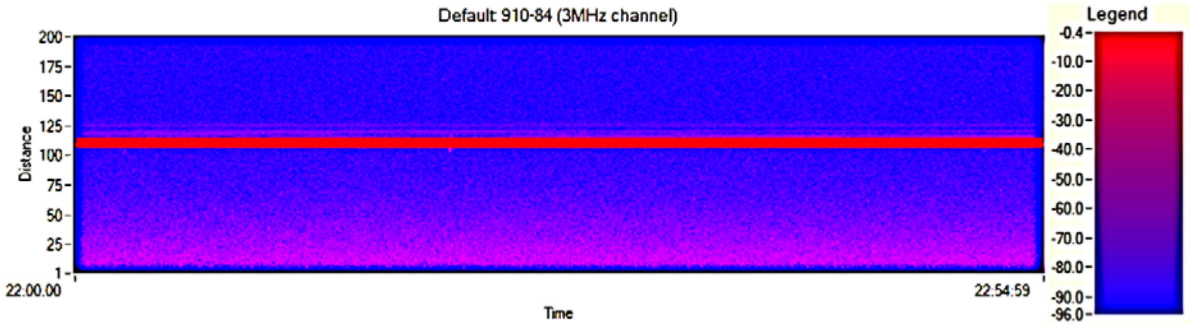


Fig. 22. Plot of 3MHz reflected signal strength from 1 1hour of data at the benthic H survey site

Although it is difficult to discern in fig. 22, at shorter distances than 110cm there is evidence of reflected signals from suspended matter in the water column. This is indicated by fine red dots on the blue background below the red line. The processing of signals of this nature can allow the size and concentration of particulate registered by the acoustic transducers of the Aquascat to be determined. A pre-requisite to the use of an instrument such as the Aquascat for a field deployment is a series of calibrations whereby particulate of known size and concentration in a controlled volume is passed below the instruments acoustic transducers. The signal strengths generated are recorded and used as reference readings. Ideally a pre and post deployment calibration of the instrument transducers should occur. This information is then used as a base reference regarding how to process the field deployment data and extract the measured particulate size and concentrations registered by the Aquascat during a deployment.

4.8 Teledyne RDI 1200KHz ADCP

The Teledyne RDI Acoustic Doppler Current Profiler (ADCP) has four acoustic transducers, with optional temperature and pressure sensors, as shown in the picture in fig. 23. In a similar manner to the Aquadopp, the device is capable of measuring water velocities at regular intervals or sample bins above the sensor array. As described previously, care must be taken when interpreting acoustically derived water velocities as a number of factors such as larger particulate above the sensor array and reflected acoustic signal strengths can affect this type of measurement. For the UK-SSB research cruise programme, the ADCP was configured to record measurements at 0.5m intervals up to a distance of approximately 25m above the acoustic sensor array. A sequence of these velocity measurements was recorded at regular intervals, typically hourly, to the ADCPs internal mass store. The ADCP included an electronic compass together with an attitude sensor for measuring pitch and roll. The ADCP was facing upwards and fitted in a gimbal on the top section of the lander frame. The use of a gimbal allowed compensation for minor orientation misalignments in the host lander frame if, for example, the lander frame was on a slope or the lander legs sank unevenly in the upper part of the seabed.

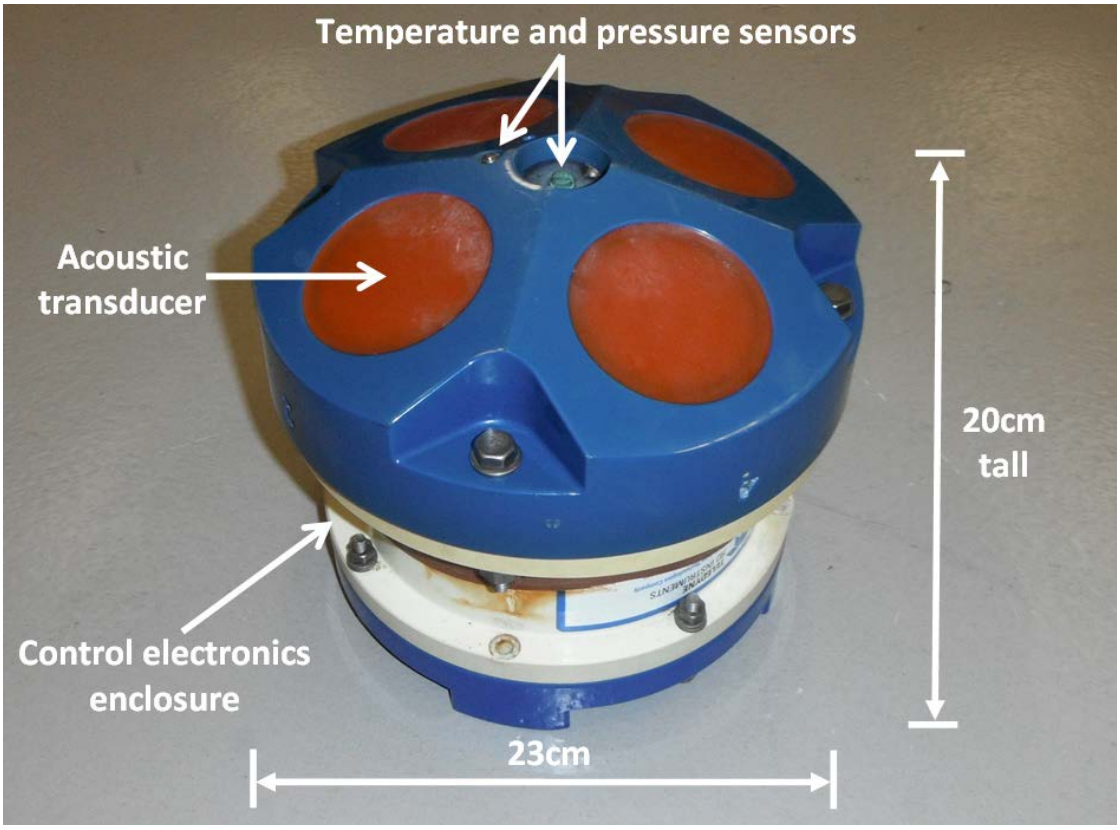


Fig. 23. The Teledyne RDI Acoustic Doppler Current Profiler (ADCP)

A plot of the recorded raw measurements during DY034 at the benthic I survey site from 24th to 30th August 2015 is shown in fig. 24. The coloured plot indicates the magnitude of the horizontal water velocity versus a time elapsed horizontal reference. The range of measurements achieved, that was typically 15-20m above the ADCP sensor array, is indicated by the vertical left hand axis of the plot. The number of the vertical 0.5m intervals or 'bins' used to take a velocity measurement is shown by the vertical scale on the right hand side of the plot.

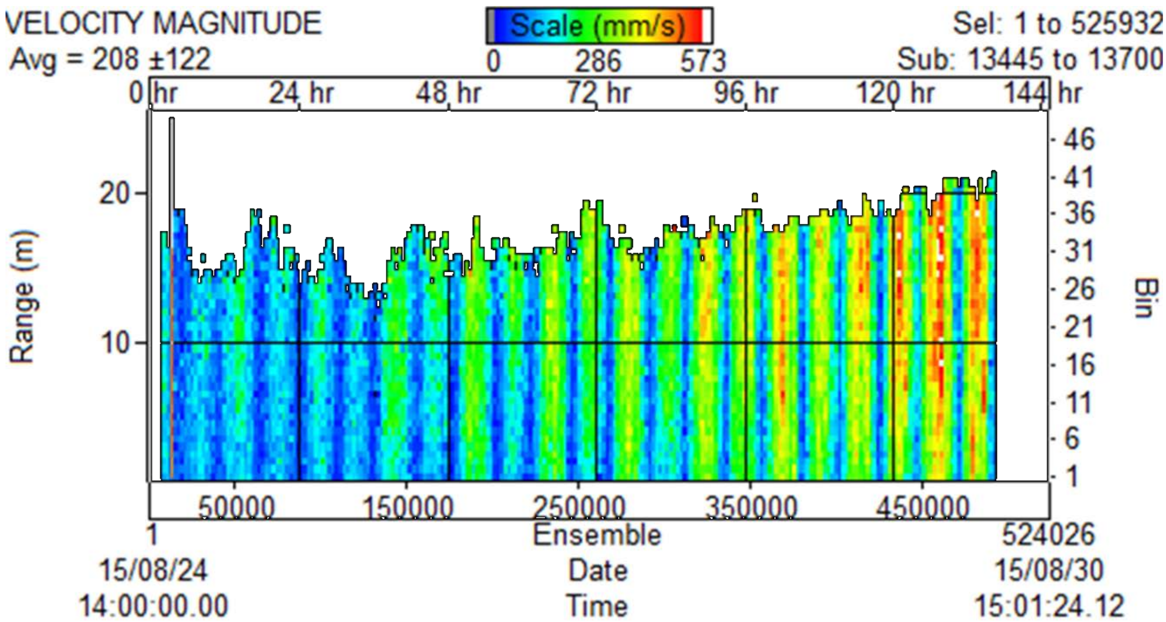


Fig. 24. Plot of velocity profiles measured by the ADCP during a DY034 deployment

4.9 McLane RAS 100 water sampler

The McLane RAS 100 uses a complex series of interconnecting pipes and multiple enclosed sample chambers to provide a facility for remotely collecting water samples, usually at timed intervals, after the instrument has been deployed. The RAS 100 includes a battery powered computer controller that can be used to sequence a series of programmable water sample volume sizes and collection times during a deployment. The RAS 100 uses an inline water pump and has a motor driven valve assembly for water sample chamber selection, together with a series of interconnecting pipes. This remote water sample collection apparatus allowed programmable volumes of seawater to be drawn into a sample collection bag, located inside a particular sample chamber, at a pre-programmed collection time. When the water sample had been collected the valve controller would then seal the inlet to the sample bag. A photograph of the RAS 100 mounted on the miniSTABLE lander frame is shown in fig. 25.

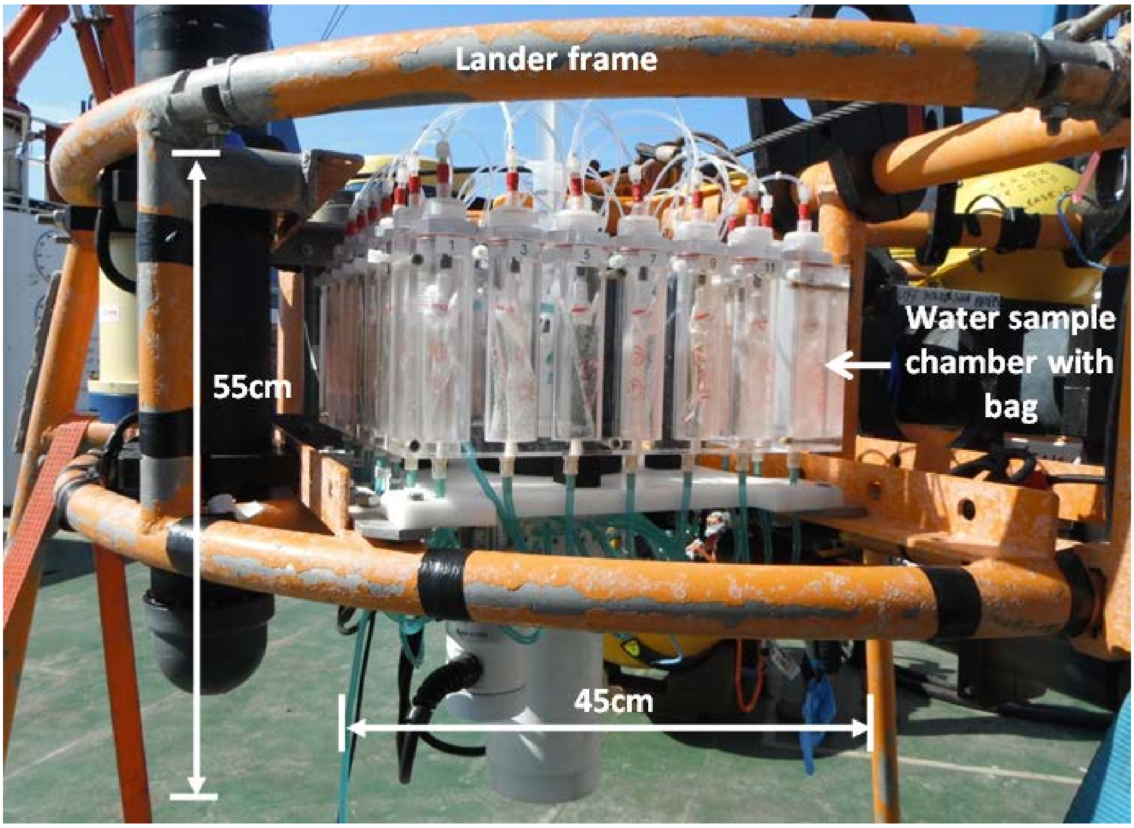


Fig. 25. McLane RAS100 water sampler mounted on the NOCL seabed based lander frame

Contained in each of the 24 water sample chambers was a sealed, clean, deflated plastic bag that was used to collect and retain the required seawater sample, as shown in fig. 26. The sample bags used had a maximum capacity of 100ml. For the RAS 100 deployments for the UK-SSB programme a small amount of preservative was placed in each sample bag prior to deployment and sample collection. This sustained the seawater state after the sample had been collected and inhibited possible contamination from such sources as bacteria already present in the collected seawater. Inorganic nutrient measurements could then be made in a laboratory after the RAS 100 had been recovered from a deployment and the sample bags were collected. Typical inorganic nutrient measurements undertaken with the collected water samples would include the levels of Ammonium, Nitrate plus Nitrite, Nitrite, Phosphate and Silicate present in the sample.

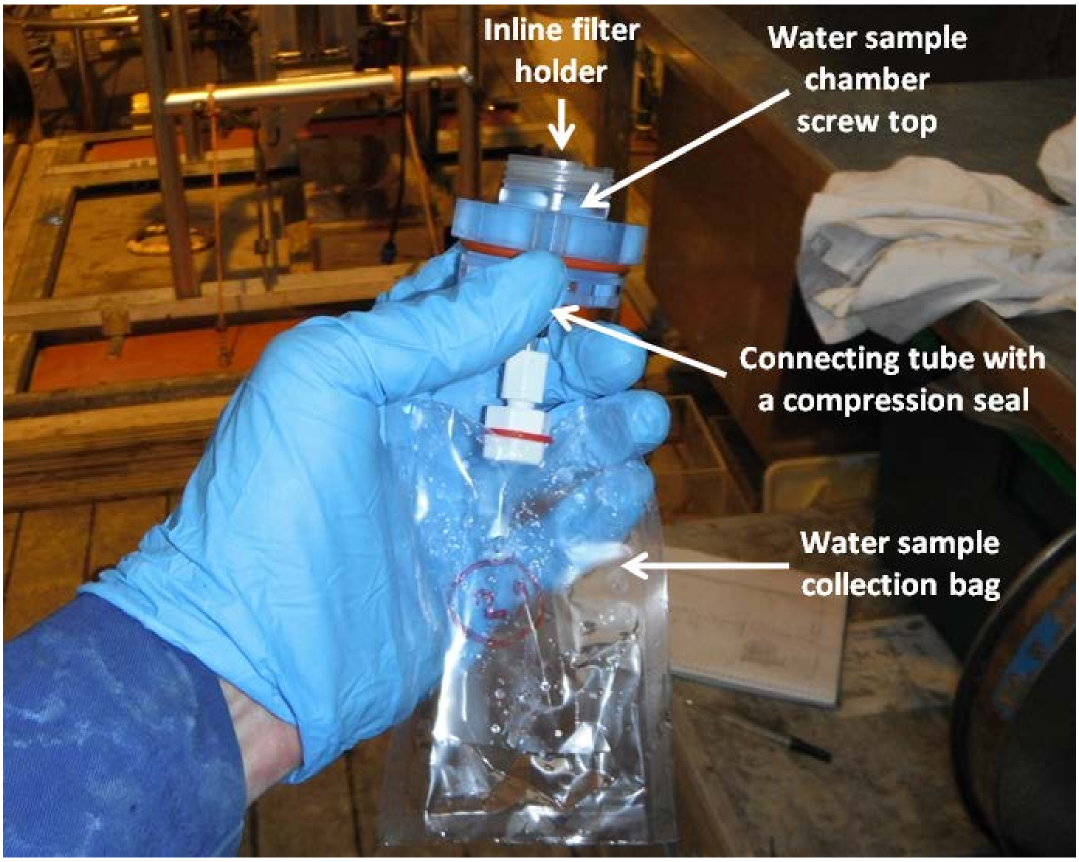


Fig. 26. McLane RAS100 water sample collection bag

Installed in-line with the inlet to each RAS100 sample bag was an accurately pre-weighed filter. These filters were used to collect any particulate matter, within a limited size range, in the seawater specimen that was pumped by the RAS100 water sample collection system into a particular sample bag. A typical seawater sample volume pumped into each RAS100 sample bag would be 80-90ml to allow a margin for extra fluids within the 100ml sample capacity of the bag. This reduced sample volume allowed for the addition of a small amount of preservative solution before the bag was installed in the RAS 100 prior to a deployment. Laboratory analysis of the recovered filters can then be used to determine an estimation of the suspended particulate matter (SPM) in the seawater. It is also possible to process the SPM filters to determine the organic and inorganic particulate matter ratios. The RAS 100 also included an automated flushing system whereby water or chemicals can be used to automatically clean the seawater inlet to the valve control and sample selection system during a deployment, before a particular sample is collected. This reduces the chances of fouling of the relatively small water sample collection inlet aperture, particularly for survey areas with high concentrations of sediment in suspension, as was the case for some of the UK-SSB research programme lander deployments.

In terms of preparing for a deployment, the RAS 100 sample chambers need to be loaded with deflated sample bags and the interconnecting pipes need to be purged of air and filled with water. This is referred to as priming before the water sampler system can be used. This can be a labour intensive, time consuming operation. Careful operational planning must be used to allow time for this if multiple ship based deployments occur, as was the case for most of the UK-SSB benthic research cruises that used the NOCL lander with a water sample collection capability. Great care must be taken when mounting, de-mounting and using the RAS 100 due to the fragile nature of the plastic couplings and interconnecting pipes used by the instrument. Prior to laboratory analysis, careful record keeping should be used to keep track of when and where samples were collected. It is also standard practice to refrigerate the water samples and SPM filters collected during a deployment in chemically cleaned containers prior to laboratory analysis. It is desirable for the water samples collected by the McLane RAS 100 system to be processed as soon as possible after they are collected to avoid possible contamination during storage or movement on and off a research vessel.

4.10 The Unisense Eddy Correlation System

For the measurement of benthic or close to the seabed oxygen flow or flux between the lower part of the water column and the seabed or suspended sediment interface, a specialist underwater 'eddy correlation' or 'eddy covariance' system was used. The use of this type of new and emerging oceanographic instrumentation system in water depths of approximately 100m or deeper, as was the case for the UK-SSB deployments of the NOCL lander system, represents novel scientific research. The Unisense version 1 eddy correlation system that was used has the capability to collect high frequency dissolved oxygen and water velocity measurements close to the seabed during a lander deployment. The key components of the eddy correlation system in the configuration used by the NOCL lander are shown in fig. 27.

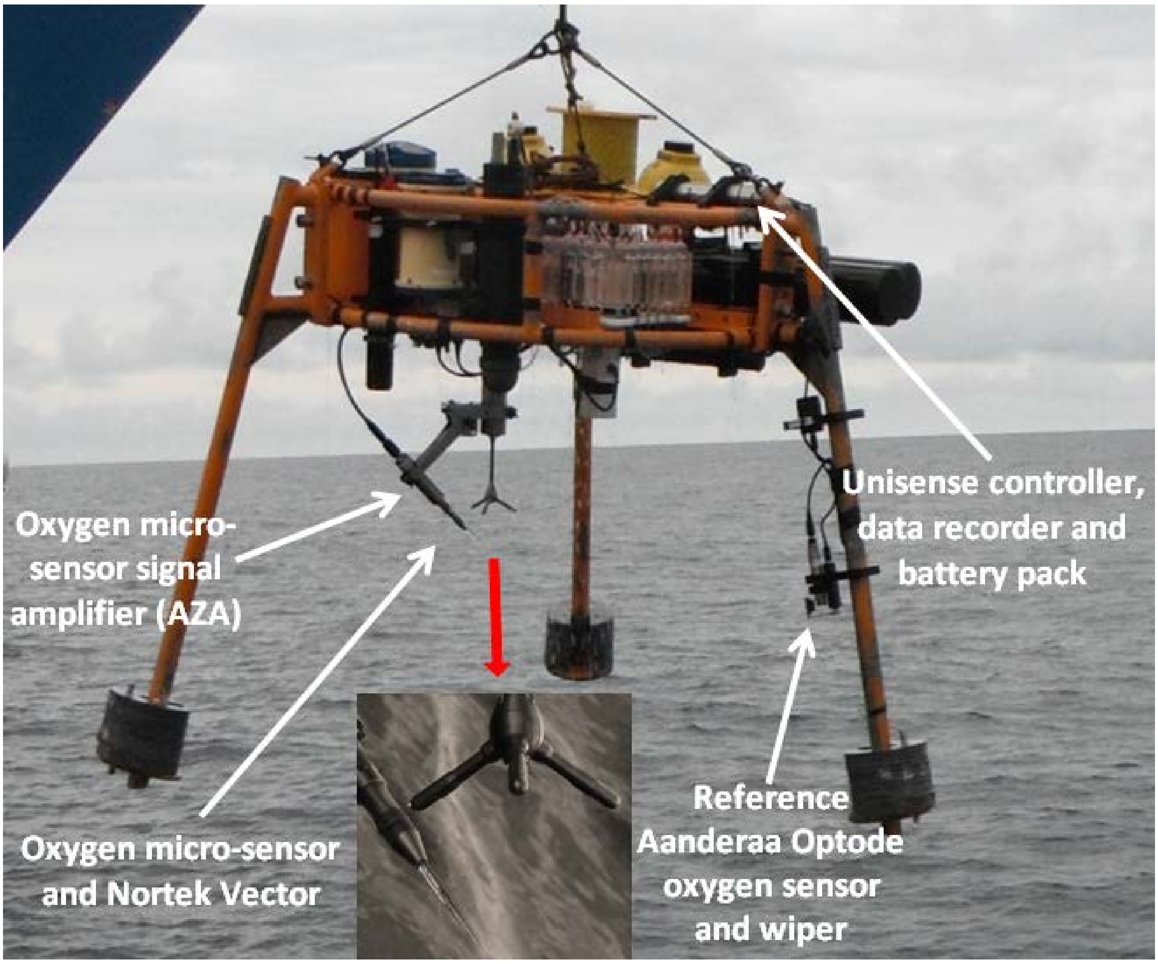


Fig. 27. The Unisense version 1 Eddy Correlation system with dissolved oxygen micro-sensor, reference Aanderaa Optode dissolved oxygen sensor and a Nortek Vector underwater velocity meter

A controller and external battery pack were installed on the upper part of the lander frame as indicated. The controller could be pre-programmed to collect and internally store measurements of dissolved oxygen from a specialist fast response micro-sensor that was housed in a fragile glass envelope. High frequency water velocity readings that were generated with a Nortek Vector underwater velocity meter were also recorded. In a similar manner to the Auadopp and ADCP the vector uses and acoustic sensor array to derive underwater velocity measurements. The glass enveloped based dissolved oxygen micro-sensor and the Nortek Vector were mounted below NOCL lander in an area towards the centre of the underside of the frame. This mounting area was chosen to be free from disturbances, particularly to water currents underneath the frame, by other sensing systems and adjacent cables or bracketry. The dissolved oxygen micro-sensor was connected to a specialist small signal amplifier or Auto Zero Amplifier (AZA), as shown in fig. 27. Interconnecting cables allowed the coupling of power and signals between the controller on the upper part of the frame and the AZA and sensor below the frame. The function of the AZA was to condition the low level signals from the micro-sensor to a form suitable for recording by the Unisense controller. A series of parameters were used by the controller to determine when readings from the micro-sensor should be collected and when adjustments to the programmable sensor signal gain of the AZA may be required. This arrangement was required to attain and sustain the desired signal levels and stability from this delicate and highly sensitive measurement system. An Aanderaa Optode dissolved oxygen sensor with an automated cleaning wiper was fitted to one of the lander frame legs, as shown in fig. 27. The Optode was mounted as closely as possible to the same vertical height above the seabed as the tip of the dissolved oxygen micro-sensor. The Optode was used to provide a slower, stable measurement of the dissolved oxygen level from a well-established commercial sensor. The intention was to provide a comparative dissolved oxygen level reading close to the eddy correlation vector and micro-sensors for reference and calibration purposes. The tip of the micro-sensor was positioned to be close to the water velocity sampling volume of the Nortek vector. This measurement sampling volume was a small area of several millimetres, which was approximately 15cm below the flat in the centre of the vector sensing head that was mounted below the lander frame. During a deployment the vector, which was powered by internal batteries, transmits measurements of water velocity to the Unisense controller. These data along with micro-sensor and Optode dissolved oxygen measurements form the scientific data set that was recorded inside the Unisense system. The Nortek Vector included an internal electronic compass for heading measurement together with pitch plus roll sensors. This allowed the attitude of the vector and subsequently the host NOCL lander system to be monitored during a deployment.

Even during a relatively short typical 1-2 day deployment of the lander a significant amount of particulate may be in suspension close to the seabed. Fouling of the Optode can occur on the dissolved oxygen sensing foil that was exposed to seawater. This may interfere with the dissolved oxygen measurement from this sensor. A commercial, automated cleaning wiper was added to prevent the onset of predominantly fine scale sedimentation that may occur on the Optode sensing foil. For the UK-SSB deployments a 2 hour Optode sensor wipe interval was used. On recovery of the lander after each of the deployments the Optode sensing foil was clean and did not show any indication that sedimentation or biofouling had occurred.

Prior to deploying a Unisense glass envelope type dissolved oxygen micro-sensor a series of preparatory and calibration procedures are required. The micro-sensor has a small amount of liquid electrolyte inside its glass envelope, which is retained inside the micro-sensor around the internal wires and sensing electrode. This needs to be purged of any parasitic dissolved oxygen. The micro-sensor should be pre-polarised, which involves applying a small electrical signal to the sensor connecting wires. Pre-polarisation also prepares the sensor for use and should be undertaken at least several hours before a sensor is deployed. In addition to this, and as close as possible to the lander frame deployment, the micro-sensor needs to be powered for at least several minutes to complete a ‘burn in’ preparatory period whereby the signal output typically reduces and then stabilises. Following this the micro-sensor was then calibrated using a solution of seawater that had been bubbled and saturated with air at atmospheric pressure. The seawater sample used was representative in terms of temperature and salinity of the local conditions where the micro-sensor was going to be deployed. The reference seawater was collected from near the seabed close to the lander deployment area using the RRS Discovery winch based precision CTD and water collection carousel system. The reference seawater was maintained at a temperature close to the seabed water temperature in the constant environment laboratory aboard RRS Discovery. Prior to use, the reference seawater was bubbled for at least 5 minutes with air at atmospheric pressure. This provided a specimen of seawater that was fully saturated with oxygen at close to sea level pressure. In addition to this a zero oxygen or anoxic reference solution was prepared and maintained at a temperature representative of that close to the seabed when the lander was deployed. The lander frame was located at the stern of RRS Discovery away from laboratory areas prior to a deployment. The calibration solutions had to be moved close to the lander preparatory area. To achieve this, the calibration solutions were transferred to open top beakers to allow immersion of the micro-sensor. As close as possible to the deployment of the NOCL lander the saturated and anoxic solution readings generated by the micro-sensor were recorded. During the calibration procedure the actual temperatures of the solutions in their respective beakers, as they were used on the underside of the lander frame, were recorded with a handheld thermometer. A similar calibration procedure was used with the solutions for the Aanderaa Optode reference sensor. If possible, and subject to the battery endurance of the Unisense system, this procedure was repeated and the sensor calibrations were recorded when the lander frame was recovered. This allowed monitoring of the calibration of the micro-sensor and Optode at the beginning and end of the deployment.

A typical endurance of the Unisense system collecting water velocity and micro-sensor dissolved oxygen measurements would be approximately 2.5 days at the maximum sample rate of 64 samples per second (64Hz). Special handling techniques for the fragile glass envelope based fast sampling dissolved oxygen micro-sensor were required to prevent damage to the sensor. As discussed in this document, careful deployment and recovery procedures were also required for the host lander system to prevent damage to the eddy correlation system and in particular the glass micro-sensor. In general the fast response micro-sensor can exhibit some stability problems in terms of drift of the absolute or total output from the sensor. However the important high frequency changes or variance in the dissolved oxygen levels can be registered by this type of sensor if it is used correctly, subject to the required preparation, careful handling and calibration. The plot in fig. 28 shows the response of a Unisense dissolved oxygen micro-sensor just prior to a deployment at the benthic G survey site during the DY030 research cruise in May 2015.

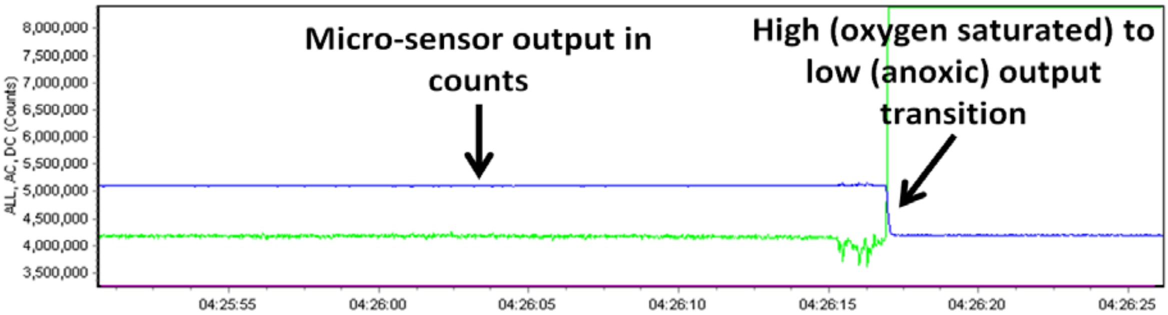


Fig. 28. The Eddy correlation system micro-sensor probe response during the DY030 research cruise

The vertical axis of the plot in fig. 28 represents the raw signal digitisation count magnitude and the horizontal axis is the time elapsed in hours, minutes and seconds. The blue trace shows the raw output from the micro-sensor in response to first a saturated oxygen solution and then an anoxic solution. The high to low transition time is less than one second, as indicated by the plot. Measurement update times of 0.3 seconds are achievable from a new, correctly handled and prepared dissolved oxygen micro-sensor. This represents a significant measurement rate advantage when compared to more established commercial dissolved oxygen sensors such as the Aanderaa Optode. The response time of the fragile micro-sensor was monitored before each deployment to make sure the sensor was operating correctly. A series of reserve sensors were prepared, and when necessary, used as an exchange before a deployment. This helped to ensure that an optimal setup of a fast response micro-sensor was used before it was deployed.

The eddy correlation technique usually involves using a moving or rolling average to provide a trend of the vertical velocity and dissolved oxygen variations close to the seabed. The product of the mean oxygen concentration and mean vertical velocity values, over an extended time scale, are then used to estimate sediment to water dissolved oxygen exchange. This interaction between vertical velocity and oxygen concentration is normally assumed to be representative of a larger area of study. Factors such as the height of the eddy correlation measurements above the seabed, underwater current levels, the seabed surface roughness, the volume of sediment in suspension and the suspended sediment consistency can affect the sensitivity of the measurement. The actual interpretation and analysis of eddy correlation data can often involve time domain and frequency domain based processing and assessment. The relative alignment and phase of the velocity and dissolved oxygen measurements, with respect to the underwater current flow, need to be taken into consideration. In addition to this, monitoring of the calibration of the micro-sensor with the slower reference readings from the Aanderaa Optode may be required. This can be used to identify drift in the absolute dissolved oxygen concentration level measured by the micro-sensor that may occur during a deployment. Special small signal processing techniques are usually required to process the raw measurement data. This is necessary to reduce any inherent noise or parasitic variation the measurement values before selecting the results that can be used for dissolved oxygen flux derivations. This can be a complex process that usually requires expert interpretation and analysis. Software tools are currently being developed to assist with this task. The estimation of underwater oxygen fluxes using this relatively new and evolving non-invasive aquatic technique is the subject of ongoing research.

Plots of the raw measured dissolved oxygen and co-located raw underwater vertical velocity, from a section of 60 seconds of the benthic A survey site measurements from the DY034 research cruise, are shown in fig. 29. A rolling or moving average has been added to each of the plots to generate the black measurement trend lines. These raw data plots would seem to indicate some level of interaction between variance in the measured dissolved oxygen concentration by the micro-sensor, and the variance in the measured underwater vertical velocity by the Nortek Vector. The plots presented in fig. 29 are intended to be for illustrative purposes only. As described previously, complex analysis of these raw data may be required to derive dissolved oxygen to sediment flux estimations.

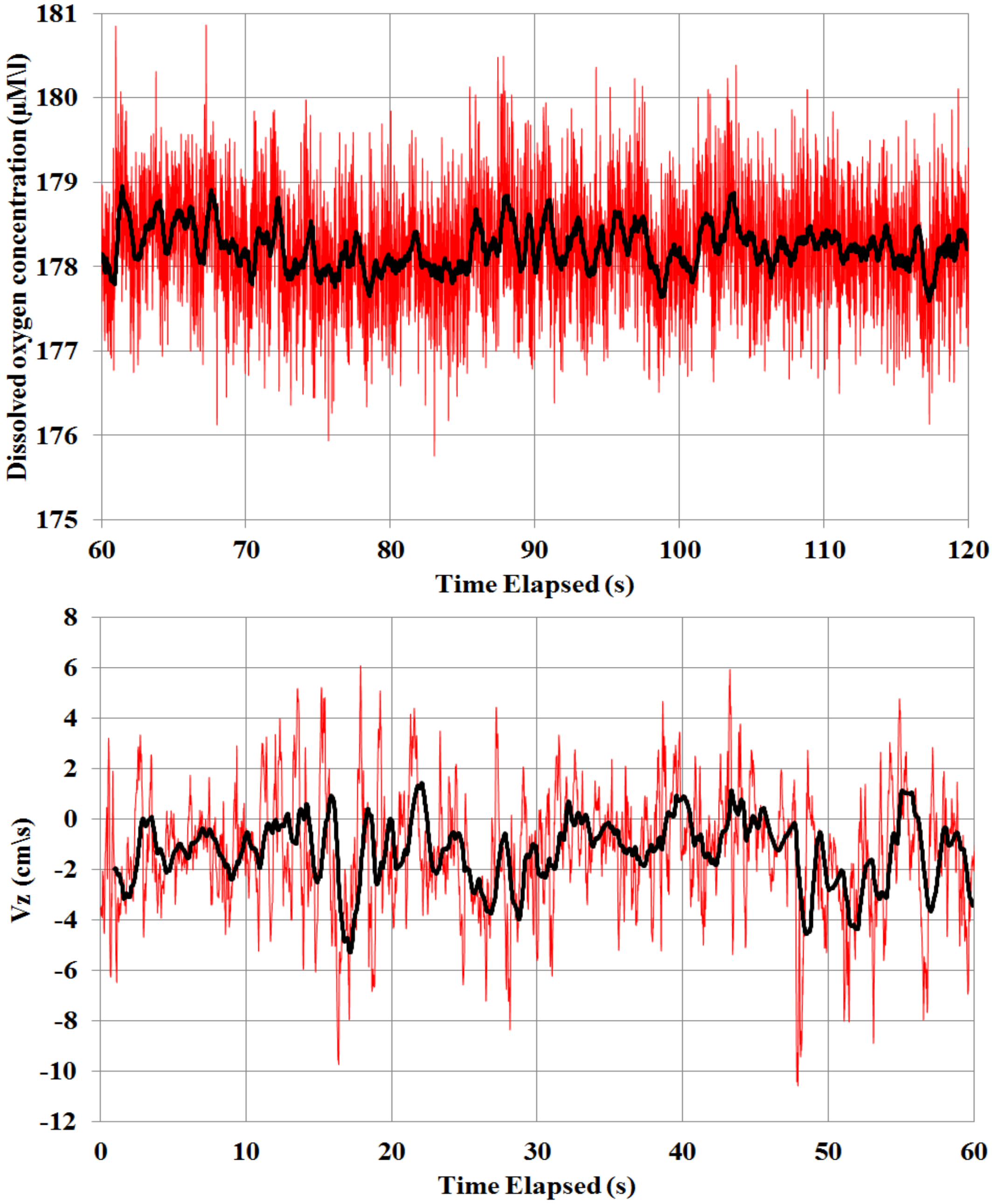


Fig. 29. Eddy correlation system preliminary raw data plots

4.11 Teledyne Benthos XT6001 Acoustic Transponders

Two Teledyne Benthos XT6001 acoustic transponders were included with the NOCL lander instrumentation suite. The transponders essentially consist of an underwater acoustic transducer, an internal glass sphere with control and interface electronics and an internal battery. An electrical connector is provided on the side of the internal glass sphere of the transponder, as shown in the labelled picture in fig. 30.

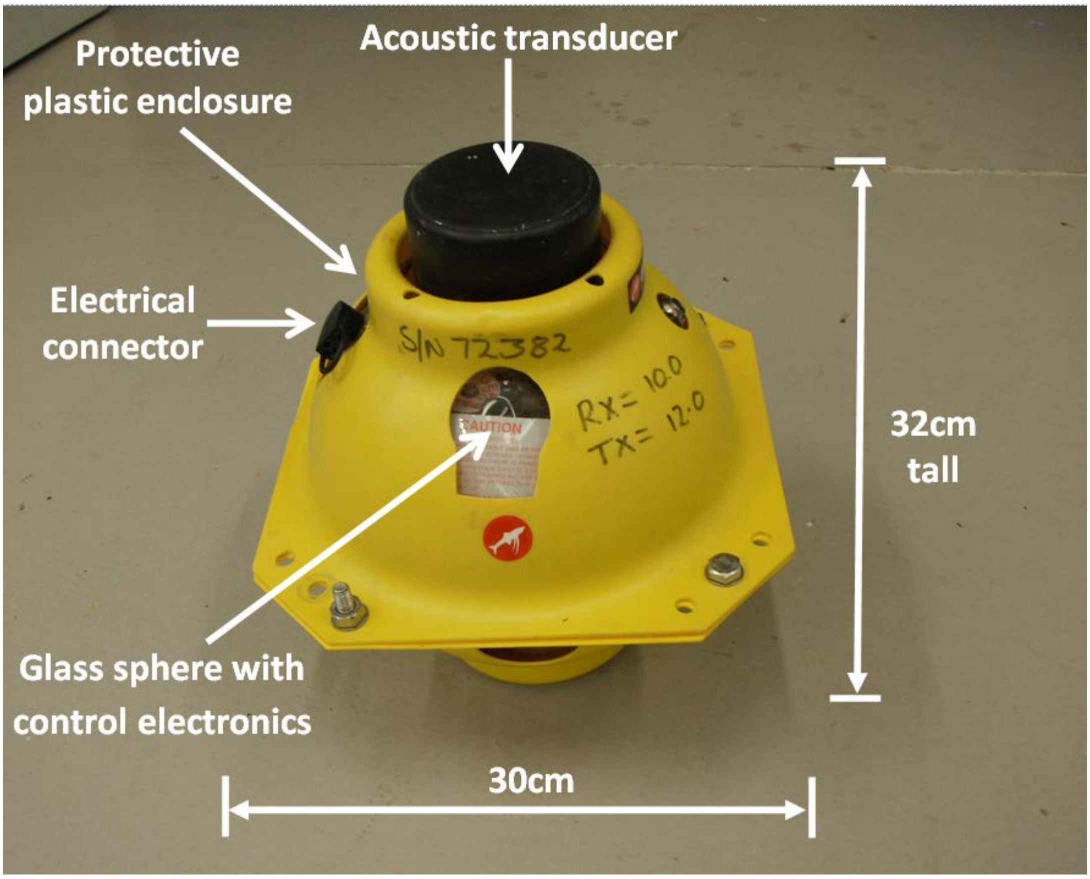


Fig. 30. Teledyne Benthos XT6001 Acoustic Transponder

The transponder was mounted inside a protective plastic cover that was supplied in two halves. The plastic cover had protruding edges with holes for fastening the covers together and the assembled transponder to external apparatus, as shown in fig. 30. A near sea surface transducer with the aid of a deck based instrumentation box and connecting cable, can be used to find the range underwater of the transponder or to activate a burn wire and subsequently operate an underwater release mechanism.

When used by the NOCL lander, the two XT6001 transponders were independently connected to a double burn wire based sprung release catch assembly. Either one of the transponders could be selected by an over the side of a ship hydrophone plus deck box to activate a burn wire and subsequently operate the mechanical release mechanism. Two transponders were used for redundancy. This provided two independent opportunities for the activation of the release mechanism to subsequently deploy the backup lander recovery line buoy. The backup recovery system has been used during the UK-SSB research cruise programme as an alternative method of recovering the NOCL lander when the main mooring failed. The XT6001 transponders were also used on numerous occasions during the UK-SSB research programme to confirm the range underwater from RRS Discovery of the deployed

NOCL lander. Problems encountered with the lander moorings and suspected trawling or dragging of the lander frame are examples of when confirmation of the lander frame range underwater was required.

5 Discussion and Summary

An overview of a complex scientific measurement system based around a seabed based lander frame has been provided in this document. The general intention is to provide a review of the motivation for undertaking the required scientific research. The key features of the instrumentation system used and a description of the evolving operational procedures to correctly utilise the lander system have been provided. One of the recently developed and more challenging measurement systems to operate has been the eddy correlation system. The estimation of underwater dissolved oxygen fluxes using this relatively new and developing non-invasive technique is the subject of current and ongoing research. A clear motivation for the use of scientific sensing systems such as this is that they provide the opportunity to undertake novel, challenging and interesting scientific research. Special operational procedures have been required to handle, deploy and recover the fragile scientific sensing systems that form the measurement system suite for the NOCL miniSTABLE benthic lander. This report is has been compiled to review the techniques used to achieve successful operation of the lander. This information is intended act as the basis for the derivation of a series of operational best practices for the future use of this type of scientific measurement system.

Calibration of the scientific sensors used during the research described in this document has formed an important aspect of the work undertaken. Close proximity measurements to a deployed lander from the RRS Discovery based scientific sensing systems have provided an essential cross calibration comparison mechanism. The over the side calibrated and profiling RRS Discovery based winched CTD system and its associated auxiliary sensors have been used extensively. The ships CTD included a capability to collect seawater samples at a specific depth to allow precision reference scientific measurements to be generated for each lander deployment. A typical minimum requirement was for a ship based CTD measurement system comparison profile, together with reference water sample collection close to the seabed, at the beginning and end of each lander deployment. The various water samples collected during the benthic survey research cruises can then subsequently be processed using precision laboratory based sensing systems and apparatus. This approach can then be employed to generate discrete precision reference measurements for lander sensor comparison and calibration. In addition to this laboratory tests of the lander scientific sensors were undertaken, when appropriate, to assess the operation and calibration of a particular sensor before and after its use. Information such as this allows the operational performance and calibration of the scientific sensors used by the lander to be monitored and assessed. Special calibration procedures were used for the dissolved oxygen measurements from the fragile glass envelope based fast response dissolved oxygen micro-sensor. This involved using reference solutions and measurements from the eddy correlation system prior to and after each lander frame deployment. This information was used to assess and monitor the calibration of the, fragile dissolved oxygen micro-sensor and the associated Aanderaa Optode reference sensor. These efforts undertaken the calibration of the scientific sensors have served to provide some level of assurance of the correct operational use of each of the lander based scientific measurement systems.

In terms of the lander deployment operations, the use of a flexible strop based standoff and acoustic release proved effective. This provided a suitable mechanism to gently lower the lander frame onto the seabed and then release the frame without sustaining disturbance or damage to delicate scientific sensing systems. The initial use of a commercial releasable spool of high strength line to recover the lander during the initial DY008 benthic research cruise proved problematic. The recovery system failed to deploy for several days after multiple attempts to operate the release mechanism. This prompted the adoption of a more traditional L shaped mooring as the primary mechanism to recover the lander. The mooring configuration used provided a physical attachment on the sea surface for the recovery of the lander frame via a ground line, seabed anchor and surface buoy, as described in appendix B of this document. Care was required when deploying the lander with a mooring to ensure that mooring line tensioning and placement does not affect the operation of the delicate, precision scientific lander based sensing systems, as discussed in appendix C of this report. Unfortunately during the DY021 research cruise an attempted recovery of the lander failed. The mooring surface float to seabed anchor coupling was broken. A backup recovery system was not implemented and a trawl of the frame to seabed anchor ground line was used to recover the lander. Although successful on this occasion, a trawl of the mooring ground line poses a risk of extensive damage to the lander instrumentation. This risk is particularly high during the initial snagging and tensioning of the mooring ground line with trawling apparatus, as discussed in appendix B, section B2 of this report. For the subsequent DY030 and DY034 research cruises a bespoke backup buoy and high strength line was implemented. This backup recovery system utilised commercial acoustic transponders and a burn wire activated underwater mechanical release. After the mooring was broken again during the DY030 research cruise in May 2015 the backup recovery buoy and high strength line system was successfully deployed to recover the lander frame. This avoided the need to resort to a ground line trawl to recover the lander, or an alternative such as a potentially expensive charter of a ship with a system such as an ROV to rescue the lander. Experience gained during this research programme has shown that line spooling based recovery systems pose a risk of failure of correct deployment. This can be due to such difficulties as possible release problems, a risk of entanglement of the recovery line, limited buoyancy of the recovery buoy or mechanism and the effects of underwater currents. For these reasons a mooring was preferred to provide a physical attachment for recovery of the lander via a surface buoy or expression. Even when the mooring surface expression coupling was accidentally broken, the option of a ground line trawl based lander recovery still existed if, for example, the backup recovery system had failed to deploy correctly.

The benthic A, H and I survey sites posed the risk of significant sinking of the lander frame into the lower density fine scale sediment that was present at the seabed. The raising of the position of the eddy correlation dissolved oxygen and water velocity sensors to counteract the anticipated amount the frame would sink into the seabed sediment proved to be an effective countermeasure. The limited time and budgetary constraints of the UK-SSB programme prompted the use of pre-emptive elevation of sensing systems below the frame.

This was demonstrated to counteract sinking into the seabed of the lander after the initial deployment and any subsequent settling of the lander frame. Alternative approaches such as wider bases on the lander frame legs were considered unnecessary and difficult to implement. If the footprint of the bases of the frame legs was increased to counteract sinking then a contingency to deal with possible increased drag from a wider leg base during the frame recovery would probably be appropriate. Systems such as extended leg base pads on hinges that are held in a horizontal orientation with limited load shear pins were considered expensive and complicated to implement. Limited load shear pins may be required to ease the task of the recovery of the frame in the event of the extended leg bases becoming lodged in or dragged along the seabed based sediment. A further concern was that a broader footprint of the lander frame leg bases may interfere with the operation of scientific sensors such as the eddy correlation system. The eddy correlation measurement can have a relatively wide field of influence or footprint that may extend beyond the limits of the underside of the frame. The seabed profile and sediment composition may also affect the eddy correlation system measurements. A narrow profile of the base of the lander legs was considered to be the simplest and most appropriate option available. If a broader, wider profile of the lander frame leg bases was used to counteract possible lander frame sinking then this may have adversely affected the eddy correlation measurements.

A complex sensing system such as the NOCL benthic lander described in this document generates a significant amount of scientific data. Each sensing system tends to produce measurements in a manufacturer specific or proprietary format. A significant amount of effort has been expended to catalogue all of the data generated by the lander deployments. Salient metadata has been used to track a particular sensor configuration and any key features that may have been observed during the operational use of that sensor. This information has been securely backed up in a form that is traceable to the original information that was recovered from the scientific sensors at the end of a particular deployment, in line with standard scientific data management best practices. Subsequent work will focus on the processing and analysis of these data to derive a quality controlled data set. The performance of the lander sensors with respect to precision reference calibration measurements will be taken into consideration. Any suspect or lower quality measurement data, when appropriate, will be excluded from the final quality controlled data set.

A rewarding aspect of this project has been that ten deployments of the lander have been completed as part of the UK-SSB research programme. This has provided a diverse set of scientific measurements that would be difficult to generate by other means. An initial review of the measurement data sets generated indicates that this information is of a high quality and suitable for scientific analysis. It is likely that the scientific surveys undertaken with the lander for the UK-SSB programme will form the basis for future research studentships and a series of high profile academic publications. Considering the fragility and complexity of the measurement systems used this clearly represents a significant achievement. A more detailed review of the key features of each of the miniSTABLE benthic lander deployments that were completed for the UK-SSB programme can be found in appendix D of this document.

Acknowledgements

Thanks to Charlie Thompson from the University of Southampton, and Briony Silburn from CEFAS, for the preliminary analyses from the RRS Discovery based DY008 research cruise core samples to determine the benthic survey site sediment compositions. Thanks Charlie for also providing the water sampler particulate filers and arranging the subsequent filer analysis. Acknowledgement is also due to Malcolm Woodward and Carolyn Harris from PML for providing the water sampler cleaning chemicals and the subsequent water sample nutrient measurements. This is really appreciated. Gary Fones from the University of Portsmouth and his colleagues are also due thanks for providing the required support for the provision of the water sample preservatives. As always, thanks are due for the superb skill and professionalism of the RRS Discovery crew for the lander deployment and recoveries, with support from NMF staff from Southampton. This high level of skill and support was essential to complete what was a challenging and ultimately highly successful series of NOC lander deployments within the UK-SSB programme series of scientific research cruises.

Appendix A – Benthic survey areas and sediment consistency

The benthic A, G, I and H primary survey used for the UK-SSB research programme had typical nominal box sizes of 1-2km x 1-2km. The deployments of the miniSTABLE lander would usually be at least 1-2 days in length with the requirement for a deployment to span at least one full 25 hour tidal cycle. The GPS boundaries for the benthic study areas are listed in table A1. Figure A1 provides a picture of the geographical locations of the benthic survey sites off the south west coast of the UK.

Table. A1. The benthic A, G, I and H scientific survey site locations

Upper left box coordinate			Lower right box coordinate		
Site A NW	51° 12.8110' N	6° 08.2190' W	Site A SE	51° 12.5400' N	6° 07.7890' W
Site G NW	51° 04.5846' N	6° 35.0862' W	Site G SE	51° 04.2114' N	6° 34.0044' W
Site I NW	50° 34.6910 N	7° 06.5550' W	Site I SE	50° 34.3170 N	7° 06.0430' W
Site H NW	50° 31.4772' N	7° 02.3628' W	Site H SE	50° 31.1844' N	7° 01.9104' W

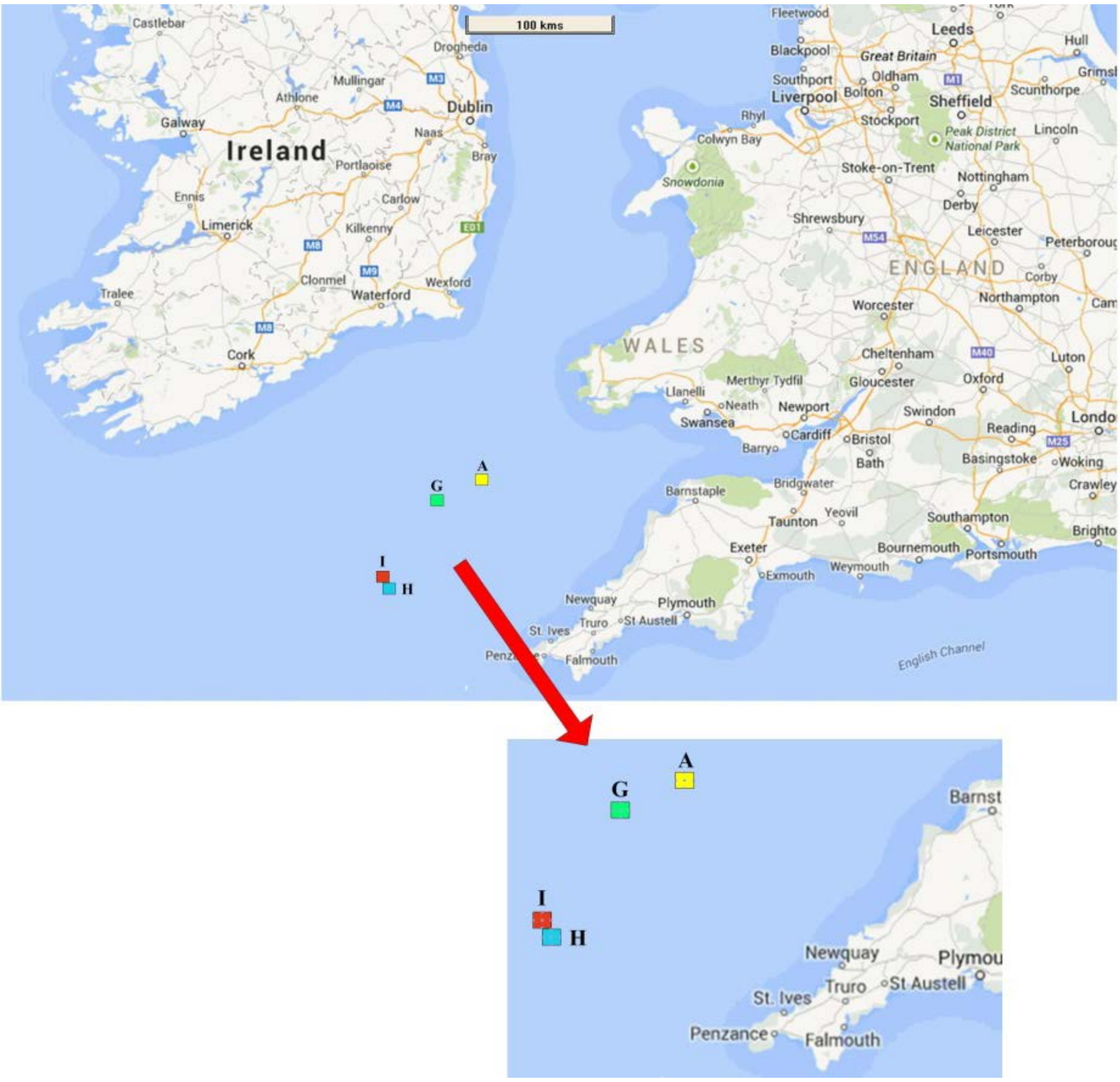
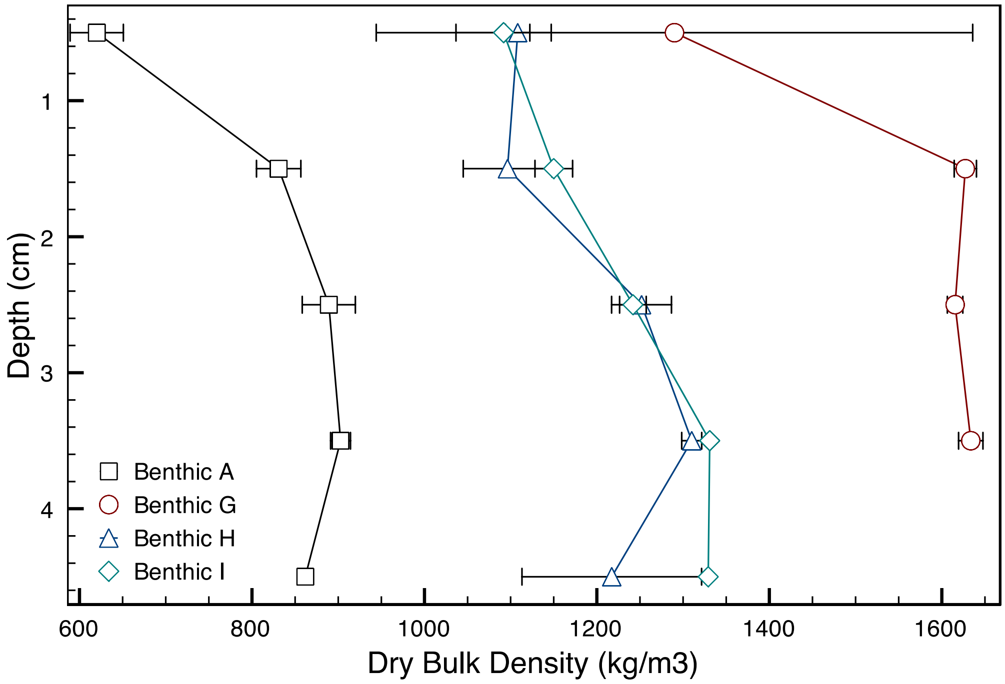
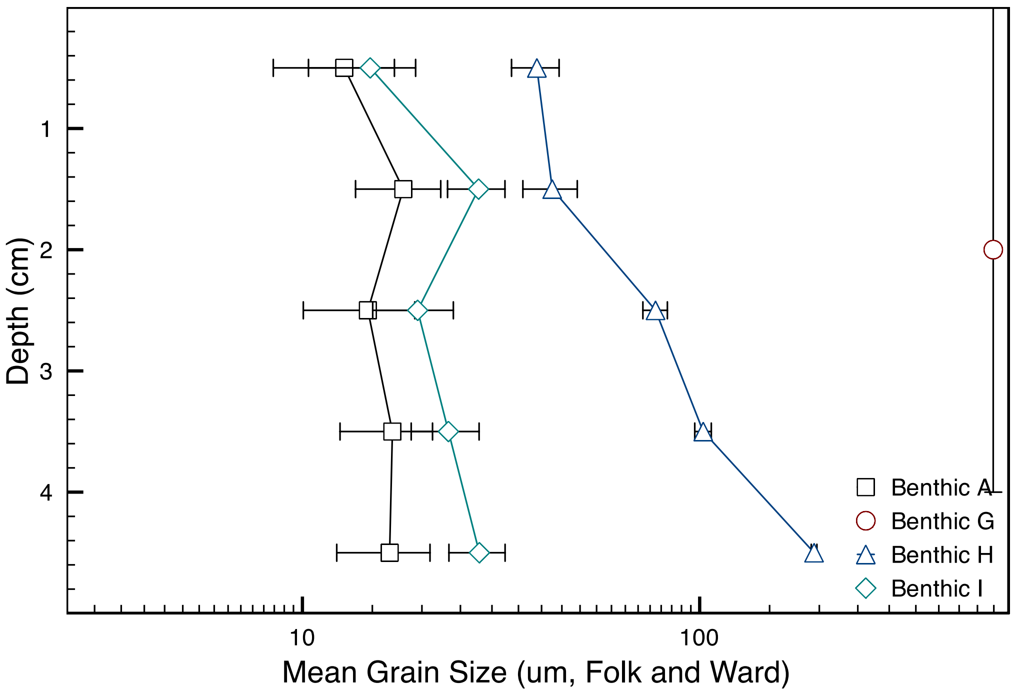


Fig. A1. The Benthic A, G, I and H survey site locations

Analysis of NIOZ seabed core samples collected during the RRS Discovery based DY008 research cruise from 18th March to 11th April 2014 as part of the UK-SSB research programme was undertaken. This was used to determine the sediment consistency at each of the A, G, H and I benthic survey sites at the seabed. Subsamples of cores retrieved at each of the benthic survey sites were dried and analysed to determine the composition of the core material and thus the seabed sediment at the time the cores were collected. A subset of this data is shown in Fig. A2 and provides an indication of the density and grain size at the survey sites to a depth of 5cm when the samples were collected.



a.- dry sediment density versus depth



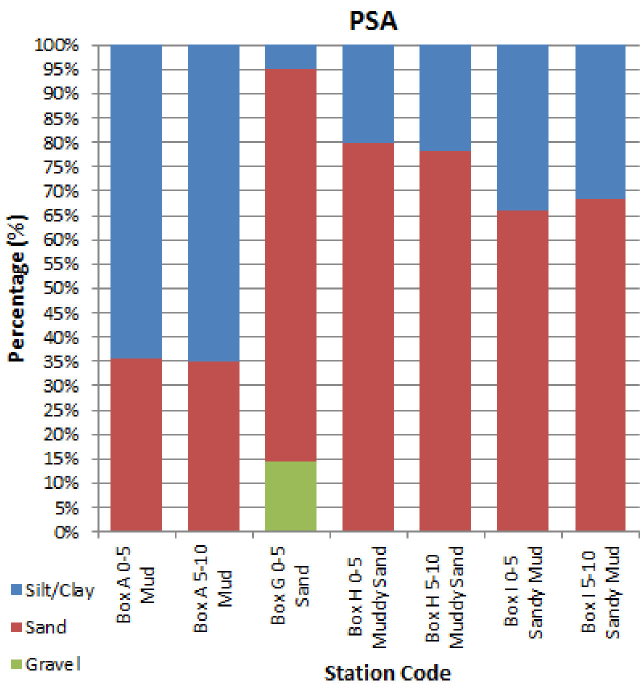
b.- estimated sediment grain size versus depth

Fig. A2. The Benthic A, G, I and H survey site sediment properties

(A subset of preliminary DY008 cruise data supplied courtesy of C. E. Thompson, University of Southampton)

The preliminary results in fig A2 indicate the relative compositions of the sediments at the survey sites. This information allowed the derivation of the general sediment properties previously presented in table 1 in the main section of this document. Other analysis relating to the porosity, permeability and the organic content of the sediment has been undertaken with, for example, the sediment at the benthic A site being the most porous, as expected. Observations when operating the NIOZ coring equipment to collect the required samples seem to confirm this. To achieve the required core depth at benthic A the least amount of ballast was required, with the most amount of lead ballast being fitted to the NIOZ coring apparatus at the benthic G survey site. This extra ballast was necessary in order for the coring apparatus to achieve the required core extraction depth at the benthic survey site G, which had higher seabed based grain size and density.

Sieve based particle analysis by CEFAS for the UK-SSB programme, using samples from rectangular or box coring apparatus, has shown the particle distributions for the benthic survey sites as shown in fig. A3. The graph and table in fig A3 show the composition of the seabed based sediment for the stated depth ranges in cm. As anticipated, the sieve based particle analysis shows the benthic A survey area to have the highest composition of finer particles of silt/clay (mud) as components of the sediment.



Station Code	% Gravel	% Sand	% Silt/Clay
Box A 0-5 Mud	0.00	35.49	64.51
Box A 5-10 Mud	0.00	34.89	65.11
Box G 0-5 Sand	14.26	80.94	4.79
Box H 0-5 Muddy Sand	0.11	79.65	20.24
Box H 5-10 Muddy Sand	0.19	78.20	21.61
Box I 0-5 Sandy Mud	0.02	66.05	33.93
Box I 5-10 Sandy Mud	0.01	68.38	31.61

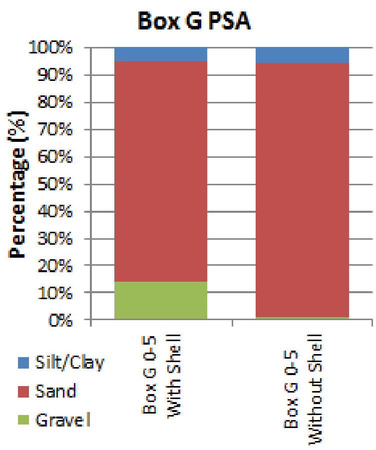


Fig. A3. The Benthic A, G, I and H survey site sediment Particle Size Analysis (PSA)
(A subset of preliminary DY008 data supplied courtesy of B. Silburn from CEFAS)

As indicated in the cart and table in fig. A3, the highest component of larger sand particles was, as expected, at the benthic G survey site. The benthic I and H sites were fairly similar and where somewhere between A and G in terms of particle sizes. Sites I and H had a higher content of finer particles than G, with an increased component of larger sand particles when compared to the benthic A survey site.

Appendix B – miniSTABLE seabed lander mooring design and operational use

A more detailed diagram of the mooring arrangement use for the miniSTABLE frame is shown in figure B1. A selection of standard 3/4”, 5/8” and 7/8” bow screw pin galvanised shackles were used to couple the various mooring components together. A 300m long, 12mm diameter steel cable with galvanised hard eyes at each end was used as the mooring seabed based ground line between the miniSTABLE lander frame and a cast steel 500kg anchor weight. A galvanised bow swivel was used to couple the ground line to the lifting point of the lander frame. The addition of a swivel was intended to counteract twisting of the ground line that may occur as the miniSTABLE frame was recovered via the ground line. Plastic fasteners and adhesive tape were used to route the ground line, during the deployment, in a preferred direction along the frame from a central lifting point and then along one of the frame legs. The intention was to keep any slack in the ground line away from the sensitive measurements below the miniSTABLE frame. These plastic fasteners were intended to break sequentially when the ground line was tensioned during recovery, allowing the frame to be hauled vertically. A plastic sleeve was added to the first 4 m of the ground line that was connected to the lander frame. This was primarily to prevent the steel ground line coming into contact with the aluminium frame to avoid the onset of galvanic corrosion. Careful fastening of the ground line was used to encourage the line to arc away from close to the base of one of the frame legs. The use of a plastic sleeve tended to stiffen the ground line to discourage looping or curling of the line close to the frame. This ground line configuration and routing is discussed in more detail in Appendix C.

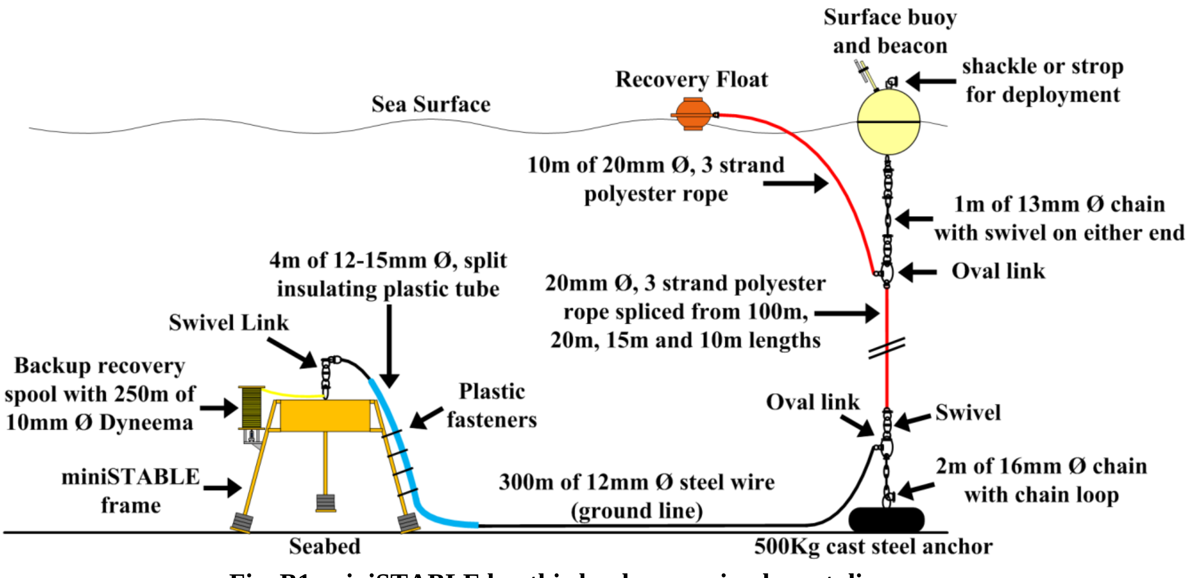


Fig. B1. miniSTABLE benthic lander mooring layout diagram

At the other end of the ground line cable a coupling to the seabed based mooring cast steel anchor weight was used. This comprised of a 2m length of 16mm diameter galvanised chain that was looped and shackled to the lifting point on the 500kg cast anchor. A galvanised oval link and bow swivel was shackled to the other end of the chain. The ground line hard eye connection was then shackled to the oval link on the cast anchor connecting chain. The addition of a swivel to the lower part of the surface to anchor polyester rope connecting line was intended to prevent twisting of the rope as the surface buoy moves around in response to surface wind, waves and underwater currents.

The required length of buoyant 3 strand 20mm diameter polyester rope was assembled from component parts to form the rope connection between the surface float to the seabed based cast anchor coupling chain. The polyester rope was supplied with soft eye connections at both ends in lengths of 100m, 20m, 15m and 10m. The rope was then spliced together with soft eyes to the required length. For example a typical working depth for the mooring would be 100m. To decide on the required length of rope the usual approach would be to add 10m of length to the nominal 100m water depth to compensate for possible tidal variations. If required further 10m or 20m lengths of rope could be added. This extended length could be used to allow the mooring to be hauled on board RRS Discovery without tensioning or snatching of the line due to such factors as motion of the mooring recovery vessel. Soft eye couplings were considered adequate owing to the relatively short 1-2 day deployments of the lander that were typically scheduled.

An oval link shackled to the top of the anchor to surface rope allowed a further buoyant 10m polyester line to be used to couple a recovery float using shackles. If required galvanised metal inserts or thimbles to ruggedize the connecting soft eyes on the sections of rope could be used. From the top of the oval link above the anchor to surface float polyester rope a 1m length of 12mm diameter chain with bow swivels at either end was used to couple the surface buoy. The use of swivels at either end of the chain link to the surface buoy was intended to prevent wrapping and entanglement of the recovery float and line with the upper part of the mooring that was close to the underside of the surface buoy. For a deployment a shackle coupling was attached to the upper part of the buoy allowing a manually operated release or sea catch to be used to deploy the buoy, usually over the stern of the ship. The recovery float buoyancy would typically be in the region of 10-20kg with 100kg of buoyancy or more for the surface float representing a common choice. A flashing light beacon with night activation was fitted to the top of the surface buoy to provide a visual warning of the presence of the mooring to shipping outside of daylight hours.

B1 – Sequence of miniSTABLE deployment pictures

To clarify the mooring operation, sequences of photographs have been added to this appendix to identify some of the key mooring operational phases. Fig B2 shows the setup of the fragile glass oxygen probe and Nortek Vector water velocity meter below the miniSTABLE lander frame. The indicated alignment reference was temporarily attached to the vector. This was used to assist with the positioning of the oxygen probe tip close to the sampling volume 15cm below the vector that was used for water velocity measurements. A picture of the NOCL miniSTABLE benthic lander frame ready for deployment on the stern of RRS Discovery is shown in fig. B3. A strop looped through the upper part of the lander frame and connected to an inline acoustic release was used to lift the lander. A crane with a wide sheaved block and a line coupled to a deck winch was used carefully and progressively vertically move the lander frame astern and then lower the lander to be deployed. As shown in the picture a favourable, benign sea state is desirable to avoid possible damage to or breakage of the delicate eddy correlation sensors below the main upper section of the lander. The wide sheave block, crane and rope routed through the block to a deck winch can be seen in the upper part of fig. B3.

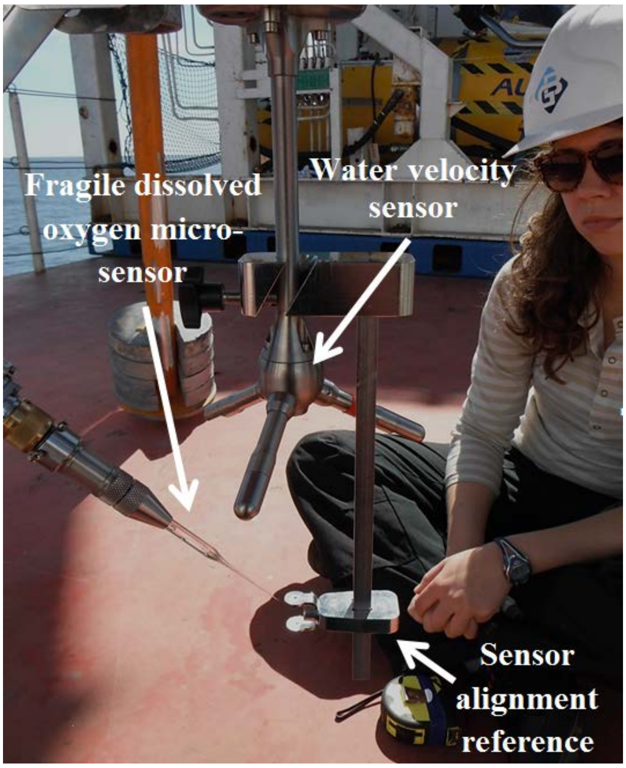


Fig. B2. Setup and alignment of the eddy correlation sensors underneath the miniSTABLE frame

Fig. B3. miniSTABLE lander frame ready for deployment

A closely controlled procedure was required to progressively deploy the lander frame while attempting to avoid degrading or damaging the fragile glass envelope based dissolved oxygen sensor below the frame. Besides the possibility of breaking the dissolved oxygen sensor the performance in terms of the sensor response time can degrade if it is subjected to mechanical vibration or mechanical shock. Therefore, careful handling of the lander is essential for a successful deployment. Using the lifting arrangement shown in fig B3 the lander frame was progressively raised, moved past the rear deck and then lowered over the stern of the ship during the deployment, as shown in fig. B4.

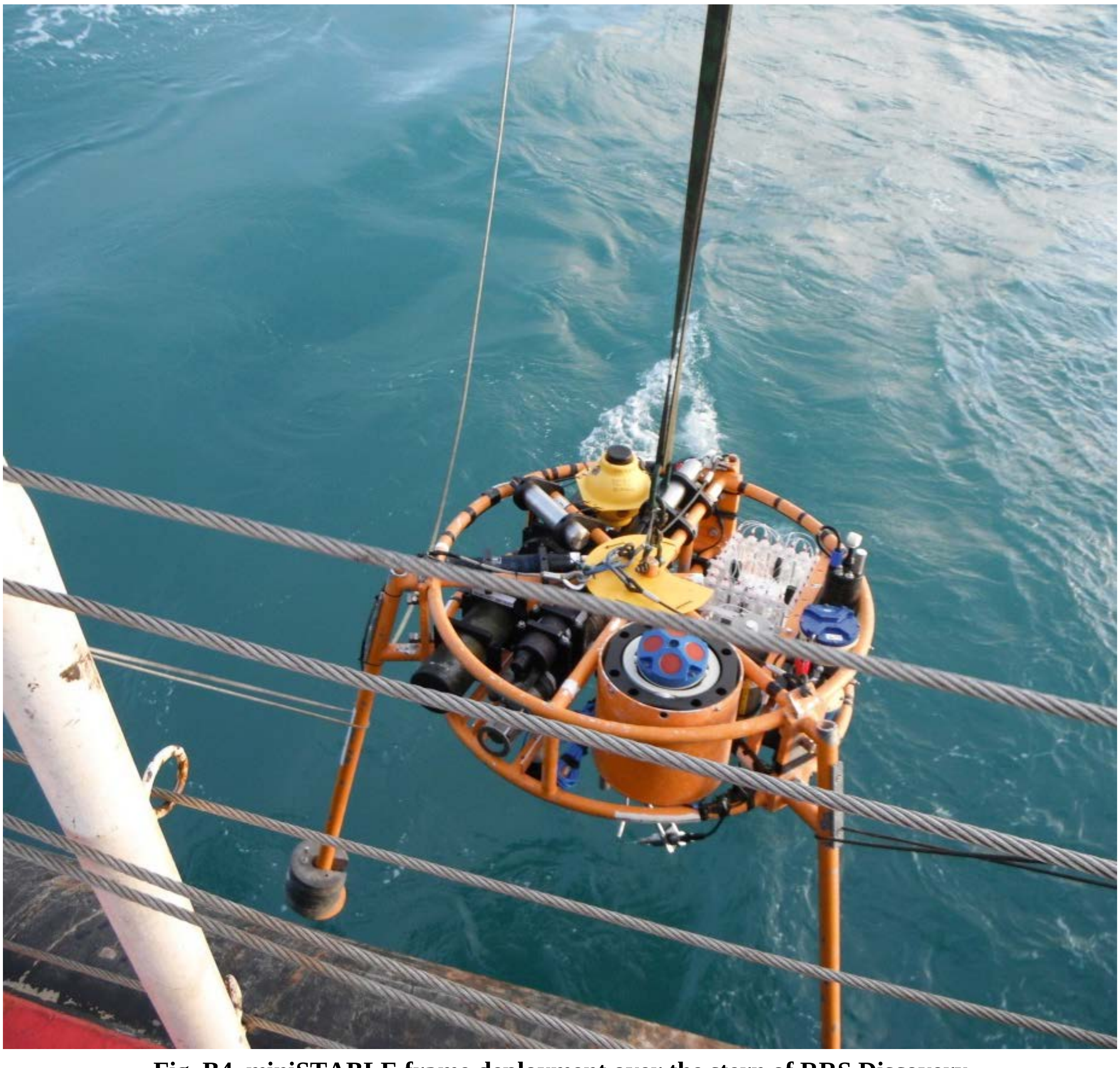


Fig. B4. miniSTABLE frame deployment over the stern of RRS Discovery

The ground line attached to the frame was also paid out from a second deck winch. A suitable amount of slack was maintained in the ground line cable to avoid tensioning of this line and influencing the position or attitude of the frame as it was lowered to the seabed. Range information from the acoustic release was provided by via a ship based over the side transducer, cable and deck unit. As the frame approached the seabed the decent rate, governed by the acoustic release line pay-out speed from a deck winch, was reduced and the frame was gently landed on the seabed. Manual monitoring of the tension in the line to the frame and range information from the acoustic inline release were used to determine when the frame was on the seabed. Extra slack was then paid out by the ship based winch controlling the frame to take the tension out of the lifting strop below the acoustic release. This avoided the ships motion from potentially tensioning or snatching the line attached to the miniSTABLE frame before the inline acoustic release could be operated. The acoustic release was then activated. The release and lifting strop were then subsequently raised and slowly moved away from the miniSTABLE central lifting point to avoid the strop snagging with the lander frame or the frame lifting assembly. When the inline acoustic release was recovered on deck, RRS Discovery slowly moved away from the frame deployment location laying the ground line from a deck winch. Care was taken to avoid any tension or snatching as the ground line was progressively laid on the seabed. Usually approximately 150-200m of ground line would be lowered to the seabed before the ship held station once again. At this stage the cast anchor, chain, oval link and swivel was attached to the other end of the ground line. The polyester anchor to surface buoy connecting rope was connected to the anchor clump and used to lower the anchor to the seabed. A swivel coupling was used with the lower part of the buoyant connecting rope that provides a link from the seabed based cast 500kg anchor to the surface buoy. The final phase of the mooring operations was to deploy the surface buoy, via a connecting chain and the recovery float plus line, as shown in figs B5 and B6. During normal operation of the mooring the surface buoy position will be influenced by underwater currents. The surface buoy will tend to follow a circular or elliptical 'watch pattern' around the position of the seabed based cast anchor with a position determined by the strength and direction of the underwater currents. Surface wind and waves may also influence the position of the buoy.

Fig. B5. miniSTABLE frame deployment over the stern of RRS Discovery

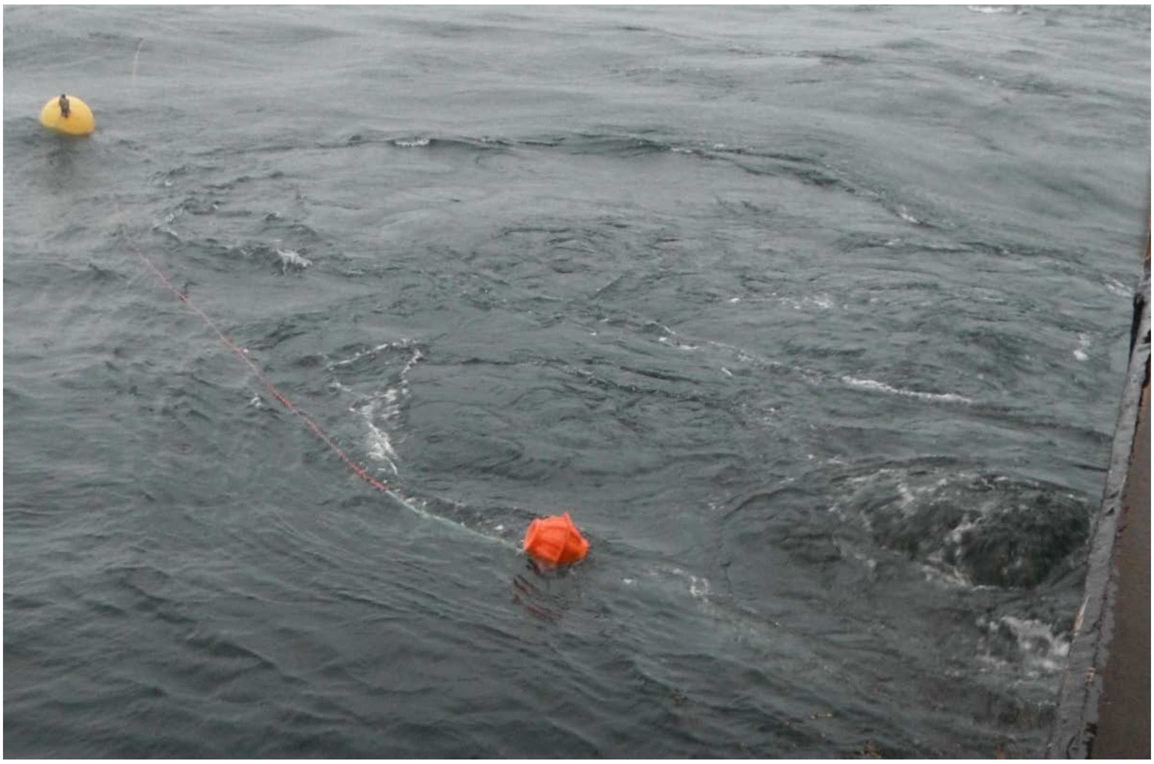


Fig. B6. Deployed surface buoy and recovery float

B2 – Trawl recovery of the NOCL miniSTABLE benthic lander

While moorings represent a standard, tried and tested, relatively robust mechanism for deploying marine instrumentation failure of or damage to a mooring can occur. During two separate deployments of the miniSTABLE frame the seabed to surface buoy polyester rope link was accidentally broken. This line breakage occurred during the initial phases of the mooring recovery. The result of this during the two separate mooring breakages was that only the surface buoy was hauled on-board RRS Discovery. The first sequence of pictures in this section summarise the operations to recover the lander frame using a trawl based approach after the first time the mooring was damaged. The general consensus at the time was that if the miniSTABLE lander was left deployed with a broken mooring then this represents a hazard to shipping. Damage to the frame could occur due to fishing and trawling activity, particularly after the surface expression for the miniSTABLE frame L shaped mooring had been removed. A dedicated rescue using a research vessel equipped with a ROV with a heavy lift capability was considered difficult to organise in the short term and likely to be prohibitively expensive.

A risk associated with a trawl recovery of the miniSTABLE lander via the ground line was that as the ground line was tensioned, damage to equipment can occur. As the frame to anchor ground line was tensioned to haul the lander towards the surface then problems may be encountered. High forces on the line can, particularly during the early phases of a trawl when the ground line tensions, possibly damage the sensitive scientific equipment mounted on the frame. With a trawl recovery it was likely that the miniSTABLE frame and the cast anchor attached to the mooring ground line would be dragged along the seabed, as the slack in the ground line was tensioned, after the initial snagging or capture by the trawl gear as it passes along the seabed. There was also a risk of entanglement of the ground line with the lander frame and its associated anchor during dragging and hauling of the frame on-board RRS Discovery. The following sequence of pictures, beginning with fig. B7, illustrate a ground line based recovery of the miniSTABLE lander frame during the RRS Discovery based DY021 research cruise that occurred in March 2015. At this stage a backup recovery system for the frame in the event of a main mooring failure had not been implemented. This was due to the time constraints involved in preparing the lander frame for use during this research cruise. Figure B7 shows the preparation of the trawling equipment on the stern of RRS Discovery.

Fig. B7. Preparation of the trawling equipment on the stern of RRS Discovery

A line from a RRS Discovery based winch with an integral transducer (dynamometer) to monitor the line tension was passed over a block on the A frame at the stern of the ship. The trawling equipment comprised of a length of large gauge chain with two trawl gear end attachments. This arrangement when dragged along the seabed was intended to snare the ground line steel cable from the broken miniSTABLE mooring. The basic configuration was for the trawling equipment to be deployed approximately 200m from the stern of RRS Discovery. As the ship slowly passed over what remained of the lander mooring, in terms of the ground line connection between the lander frame and the cast anchor on the seabed, the intention was to snare or capture the ground line. A typical trawling speed would be less than 1 knot. Ship based displays as shown in fig. B8 were used to provide key information such as the ships position, the length of the trawl line and the tension on the trawl line during the procedure.

The picture in fig B9 shows the hauling of the trawling equipment after a successful ground line capture, whereby after the ground line has been snared and the tension between the ground and trawl equipment has been sustained. This allowed the ground line to be hauled on-board RRS Discovery. As shown in the picture, the L shaped mooring steel ground line has been successfully snagged by the inner part of the trawling gear and the tension on this line has been sustained as the trawling apparatus was slowly hauled to the surface. This provided a physical link to the seabed based lander and anchor that could be used to recover the remainder of the mooring. Mechanical fasteners were added to a section of cable on each side of the trawling equipment and these fasteners were then securely connected to the stern of ship. The ground line steel cable between these fasteners was then separated and a hard eye was created on each side of the separated ground line. A shackle coupling between a line from a deck based winch that was routed over a wide sheave block, that was suspended from the A frame on the ship, was then used to haul the remainder of the mooring on-board RRS Discovery. The subsequent movement of the A frame away from the stern of the ship allowed the remainder of the ground line to be hauled vertically away from the stern of the ship, as shown in fig. B10.

Fig. B8. Monitoring of the ships position, the trawl line length and the trawl line tension

As shown in fig. B10, during the trawl process the ground line had moved underneath the lander frame and entangled around a pair of large metallic battery cases that were protruding and securely fastened to the frame with robust saddle type clamps. This allowed the forces involved in the trawling process, particularly the initial tensioning of the ground line, to be withstood without significant damage to the sensitive scientific instrumentation systems fitted to the frame. As the miniSTABLE benthic lander frame was slowly raised, a crane, lifting strop, tag line and boat hook were used to carefully wright the orientation of the frame for subsequent recovery and landing on the stern of the ship as per the picture in fig. B11.

Fig. B9. Recovery of trawl equipment with the miniSTABLE to cast anchor ground line snagged

Fig. B10. Recovery of the lander with the ground line wrapped around one of the larger battery cases that protruded from the lander frame

Fig. B11. A Crane, strop, stay line and boat hook used to re-orientate the frame during the recovery

Fortunately, only minor damage to some of the cables on the frame was sustained during the trawl recovery and remarkably the fragile eddy correlation sensors below the frame were still intact, including the glass envelope based dissolved oxygen micro-sensor, as per the picture in fig. B11. The final part of the process was to recover the cast anchor and carefully haul in the remainder of the broken cast anchor to surface buoy rope, as per the photograph shown in fig B13.

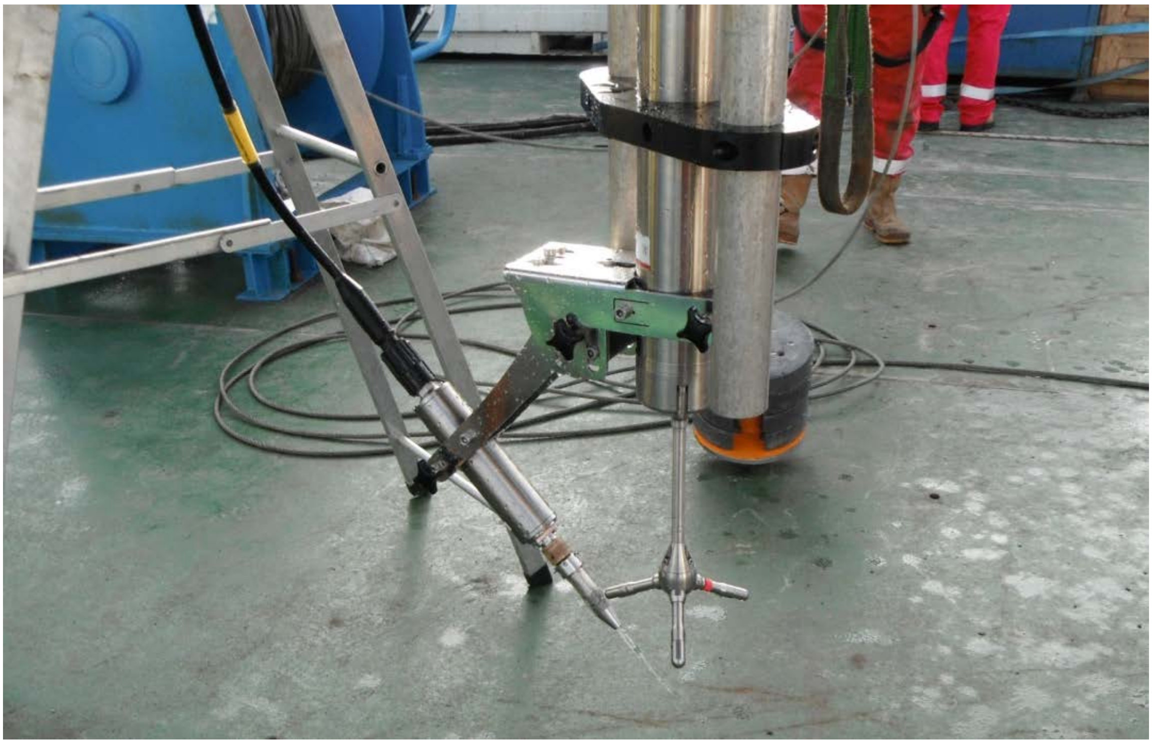


Fig. B12. The glass oxygen micro-sensor and Nortek Vector from the eddy correlation system underneath the frame were still intact after the trawl recovery

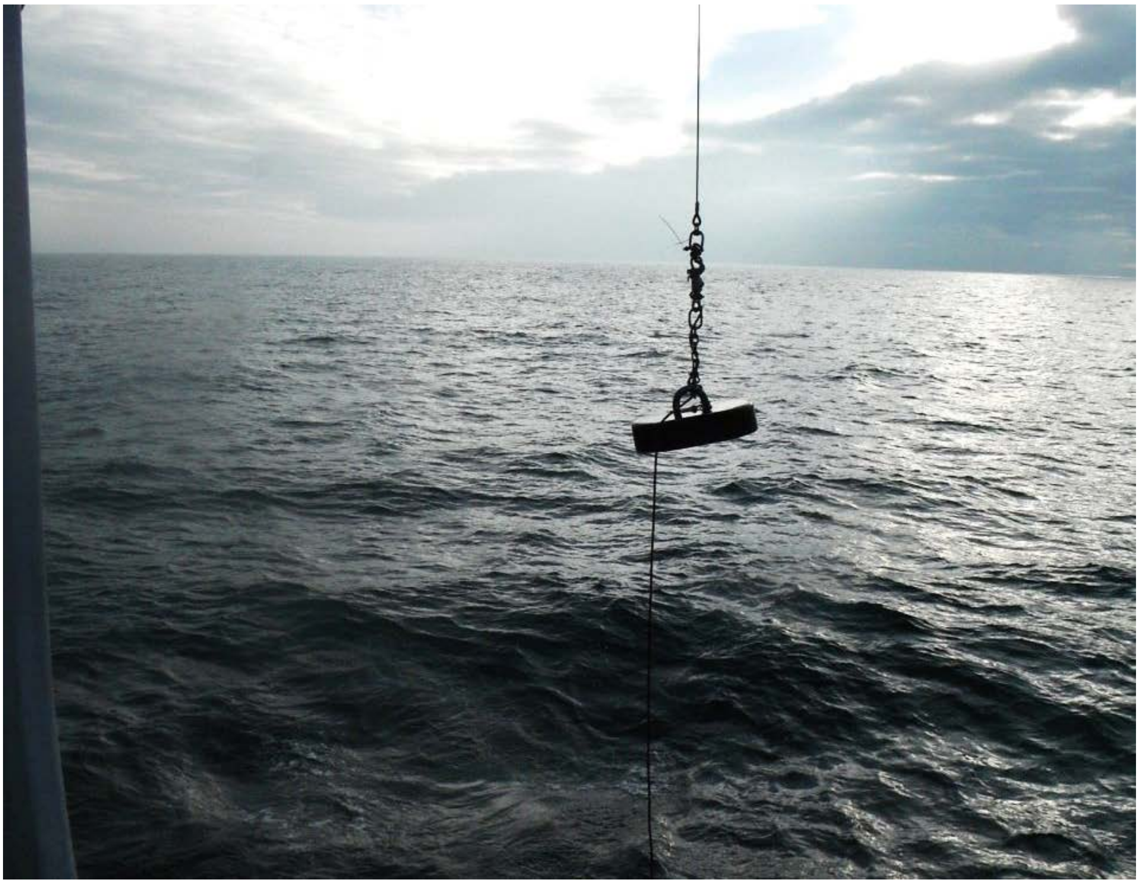


Fig. B13. Cast anchor and broken anchor to surface float recovery

B3 – Backup recovery system implementation and first use

The failure of the mooring during the DY021 research cruise in March 2015 prompted an investigation into techniques to rapidly implement a backup miniSTABLE recovery system. This backup recovery option was required to be available for the future research cruises in the UK-SSB programme that would require the use of the lander frame and its associated suite of scientific instrumentation. The National Oceanography Centre at Liverpool (NOCL) had been experimenting with recovery systems based upon releasable buoys and coils or spools of line. The type of line used was neutrally buoyant and strong enough to provide a direct heavy lift capability. Based upon the mooring failure that had occurred during the DY021 research cruise in March 2015 a secondary, reserve recovery system was implemented for the DY030 research cruise in May 2015 and the final cruise in the UK-SSB research programme DY034 that occurred during August to September 2015. Previous experiences with spooler based buoy and line recovery systems had been problematic due to suspected release problems, suspected limited recovery buoy or float buoyancy limitations and possible spooler line entanglement. Based upon this, it was decided that a mooring should remain as the primary mechanism for deploying and recovering the NOCL benthic lander frame. A buoy or float and line based system should only ever be used as a backup recovery mechanism. As demonstrated by the sequences of trawling pictures in this appendix, even a broken mooring can offer an alternative mechanism to recover the miniSTABLE lander frame. If a spooler or float and line based recovery system fails to deploy then alternative recovery options can be severely limited if a mooring has not been used. A picture of the backup recovery system, which was based upon a releasable float with a coil of 250m of high strength line, is shown in fig. B14. The position of the two Benthos XT6001 acoustic transducers that were used is indicated in the photograph. To the right of the acoustics in the picture the backup float and spool of line can be seen, which was located on the side of the lander frame. A bracket below the spool on one of the miniSTABLE lander legs provided support for the backup recovery float in addition to a double burn wire release mechanism. This release can be activated underwater by any one of the XT6001 transponders in response acoustic commands issued by a ship based near sea surface hydrophone, cable and deck based control unit. As previously described, two acoustic transponders were used to add redundancy into the release design.

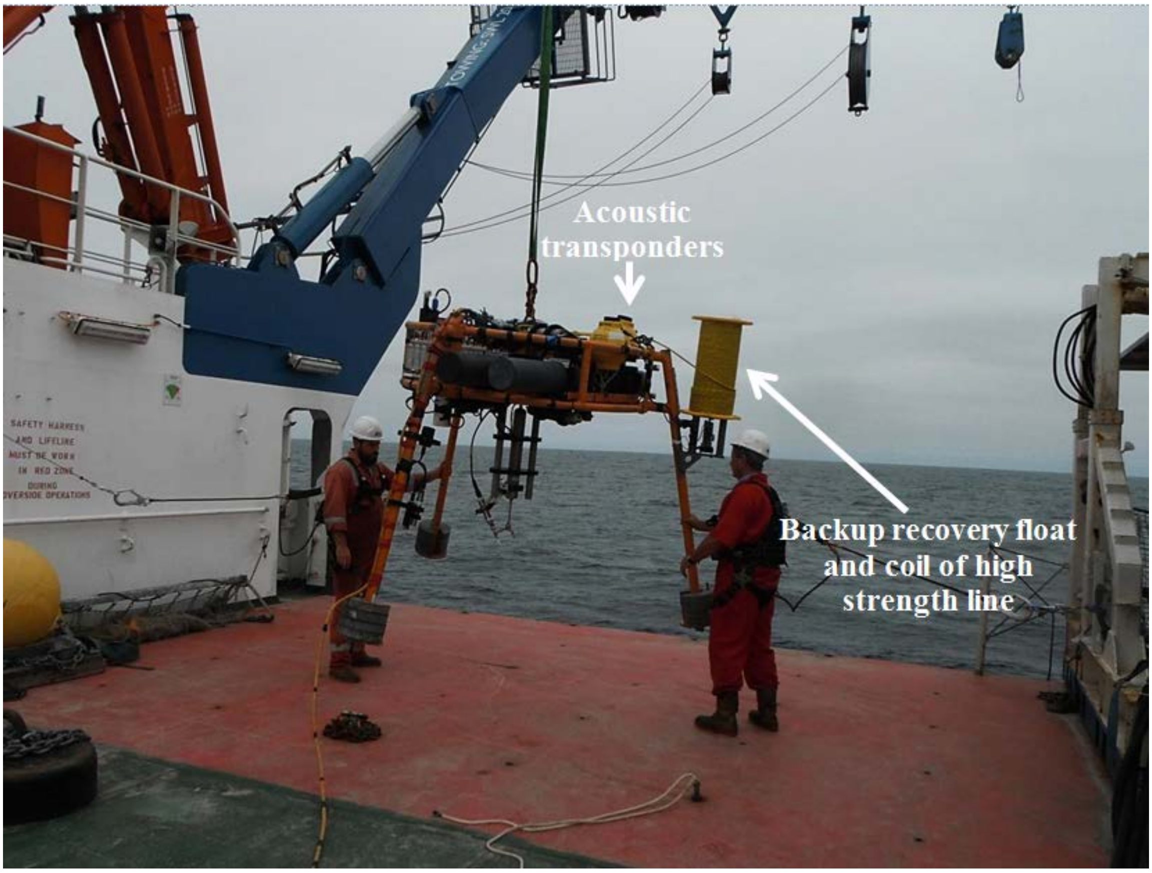


Fig. B14. Deployment of miniSTABLE benthic lander frame with a float and a spool of high strength line to form a backup recovery system

Unfortunately, during the RRS Discovery based DY030 research cruise in May 2015, the miniSTABLE mooring seabed anchor to surface float polypropylene line was damaged and a direct mooring based recovery was unsuccessful. To avoid the possibility of damage to the miniSTABLE frame via the risks described previously with a ground line based trawl recovery, the backup buoy and line system was used. On the approach to slack water with low underwater currents one of the two buoy release burn wires was activated. Status information from an over the side hydrophone connected to a Benthos deck unit revealed that, several minutes after the burn wire activation, the release wire had burned through. Following this, after approximately 35 minutes the buoy surfaced, as shown in fig. B15. When this occurred the 250m long high strength line between the miniSTABLE frame on the seabed and the backup recovery buoy on the sea surface was fully deployed. This clearly represented a potential entanglement risk with the RRS Discovery propulsion systems. The ship progressively approached the surfaced buoy, maintaining the buoy position close to the stern of the ship until the surface buoy could be snared with a grapnel and lifted on-board the rear starboard side of the ship. At this stage the line from the buoy was moved to the stern of the ship and coupled to a deck winch via a line running over a wide sheave block attached to one of the ships cranes. The crane was extended over the stern of the ship and the line was slowly hauled to recover the frame, as shown in fig. B16. As expected, the mooring ground line steel cable from the seabed based steel anchor was still attached to the upper lifting point on the miniSTABLE frame, and this represented a further tensioning and entanglement risk. Care was taken to avoid any sudden movements of the frame that could result in tensioning or snatching of the recovery line or ground line during hauling and the ship was maintained on station during this process. This represented the first time the buoy and line spooler based recovery system had been tested since it was installed on the upper part of a side leg of the miniSTABLE lander frame. The scheduling of the UK-SSB research cruises, together with time and budgetary constraints, prevented field trials from occurring with the backup recovery system before it was implemented.

Fig. B15. Backup recovery float on the surface with the 250m frame to float line fully deployed

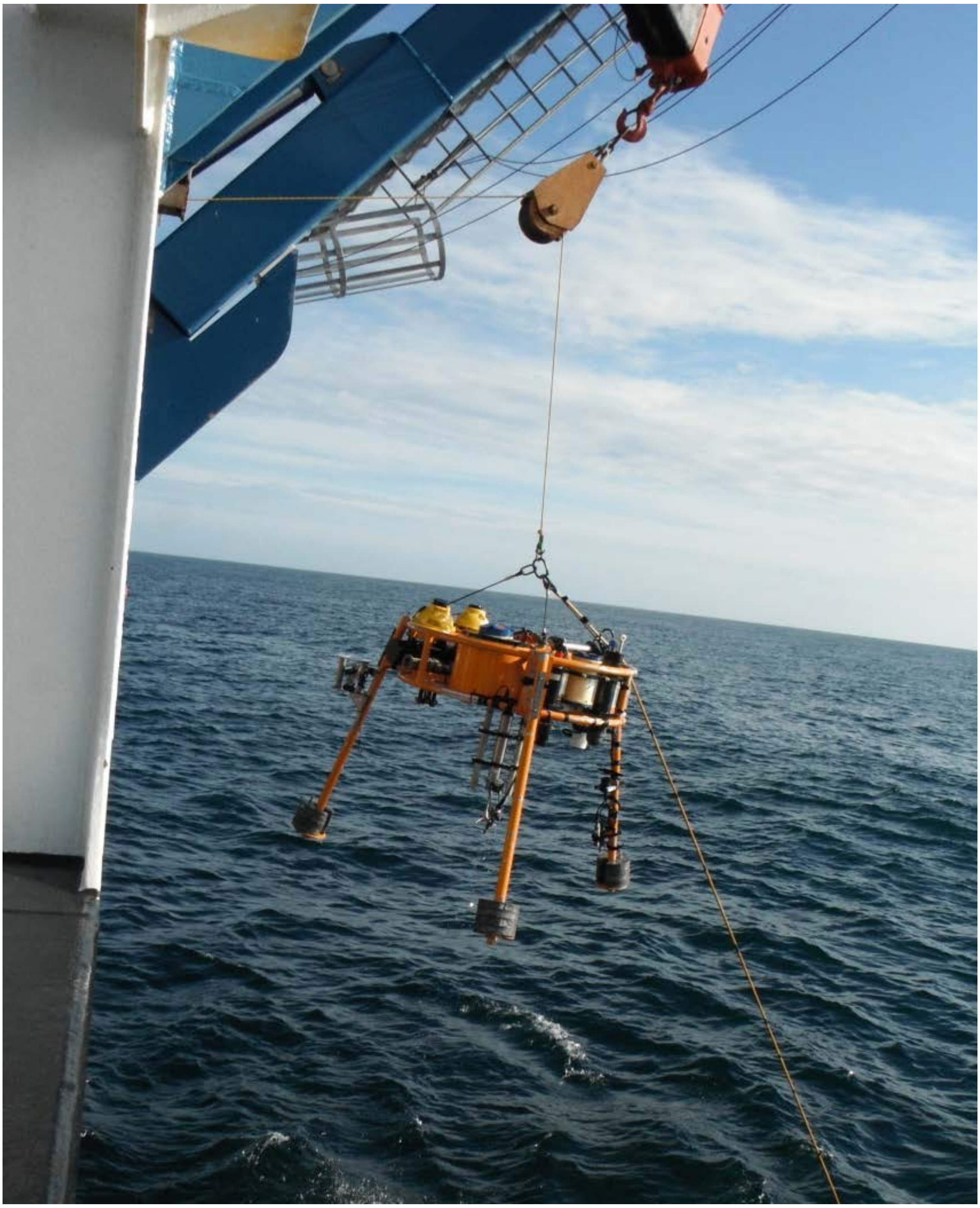


Fig. B16. Recovery of the miniSTABLE frame with the mooring ground line still attached

B4 – Mooring surface float and recovery arrangement

A problem that did tend to affect the mooring arrangement for the lander recovery was entanglement of the recovery line with the surface float and buoy beacon mounting arrangement. This resulted in difficulties with the retrieval of the recovery float and subsequently lifting of the surface buoy to access the mooring couplings on the underside of the buoy, as shown in fig. B17. During a deployment the movement of the smaller recovery float relative to the surface buoy tended to lead to wrapping and entanglement of the recovery line around the surface buoy.

Fig. B17. Recovery float and line to surface buoy entanglement during the DY034 research cruise

An alternative arrangement was trialled during the DY030 research cruise in May 2015 that used fastening of the recovery line to a chain link below the surface buoy. At either end of this chain link a swivel coupling was installed to reduce the likelihood of recovery line entanglement. The actual recovery line was fastened just below the upper swivel link, immediately below the surface buoy. A 10kg lead weight was also fastened to the lower part of the chain below the surface buoy to encourage the beacon light and mounting post to adopt a more vertical orientation. This tended to improve the surface buoy alignment during a deployment when wind, waves, underwater currents and the load of the underwater mooring caused the surface buoy positon to vary.

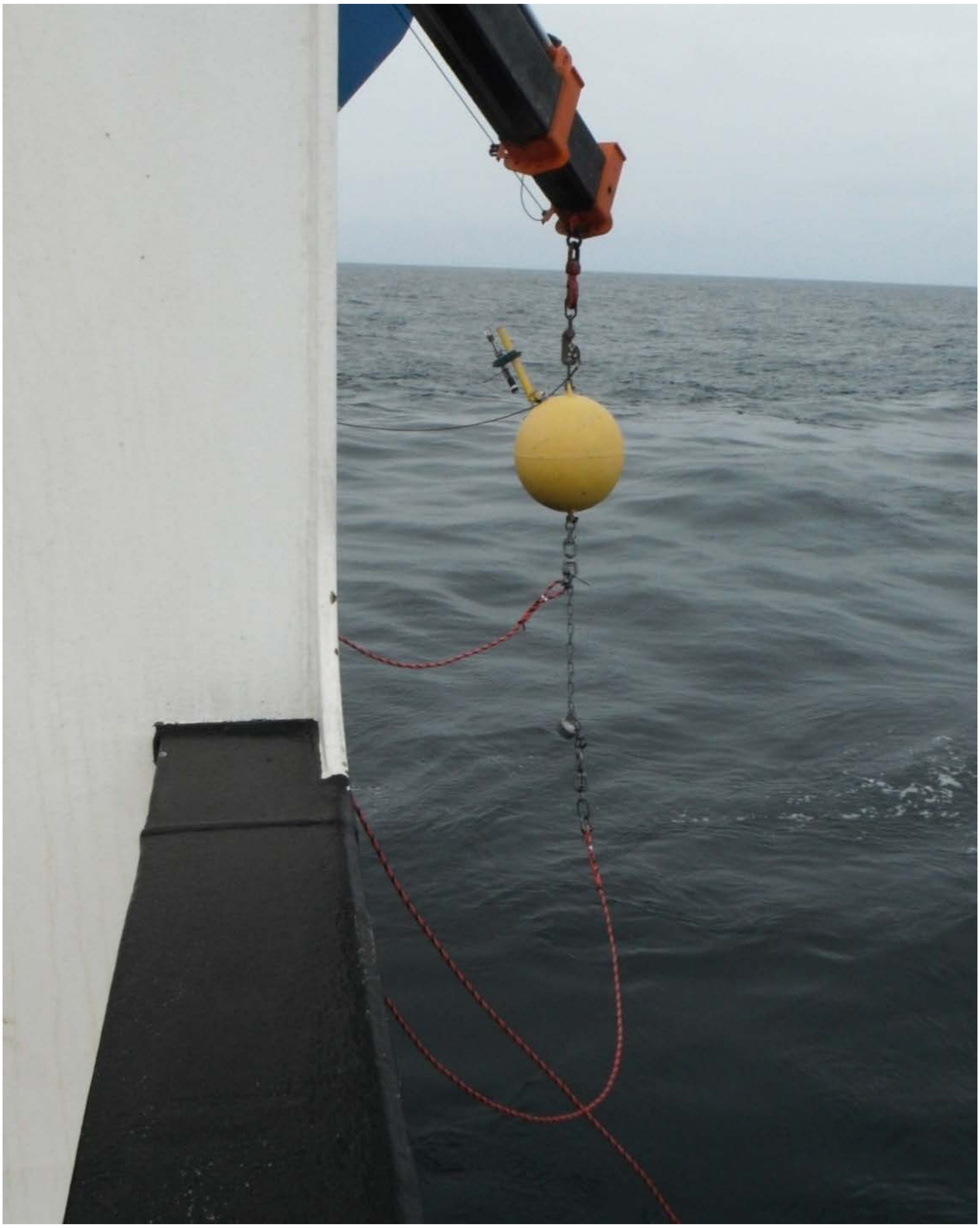


Fig. B18. Modified mooring arrangement used during the DY030 research cruise to discourage recovery line entanglement via an underside chain and double swivel link coupling

An improved arrangement for future deployments could be to employ an alternative surface expression in the form of a toroidal surface float within a mounting frame, as per the example in the photograph in fig. B19. This type of surface float is commonly used for marine instrumentation based mooring applications and would typically be in the order of 1-2m in diameter. Usually the buoyant toroidal float would be fastened to a supporting metal frame to allow instrumentation mounting and mooring coupling. A beacon or solar light can be placed in a more visible raised position on the part of the mounting frame that is attached to the upper part of the toroidal float, as per the example in fig. B19.

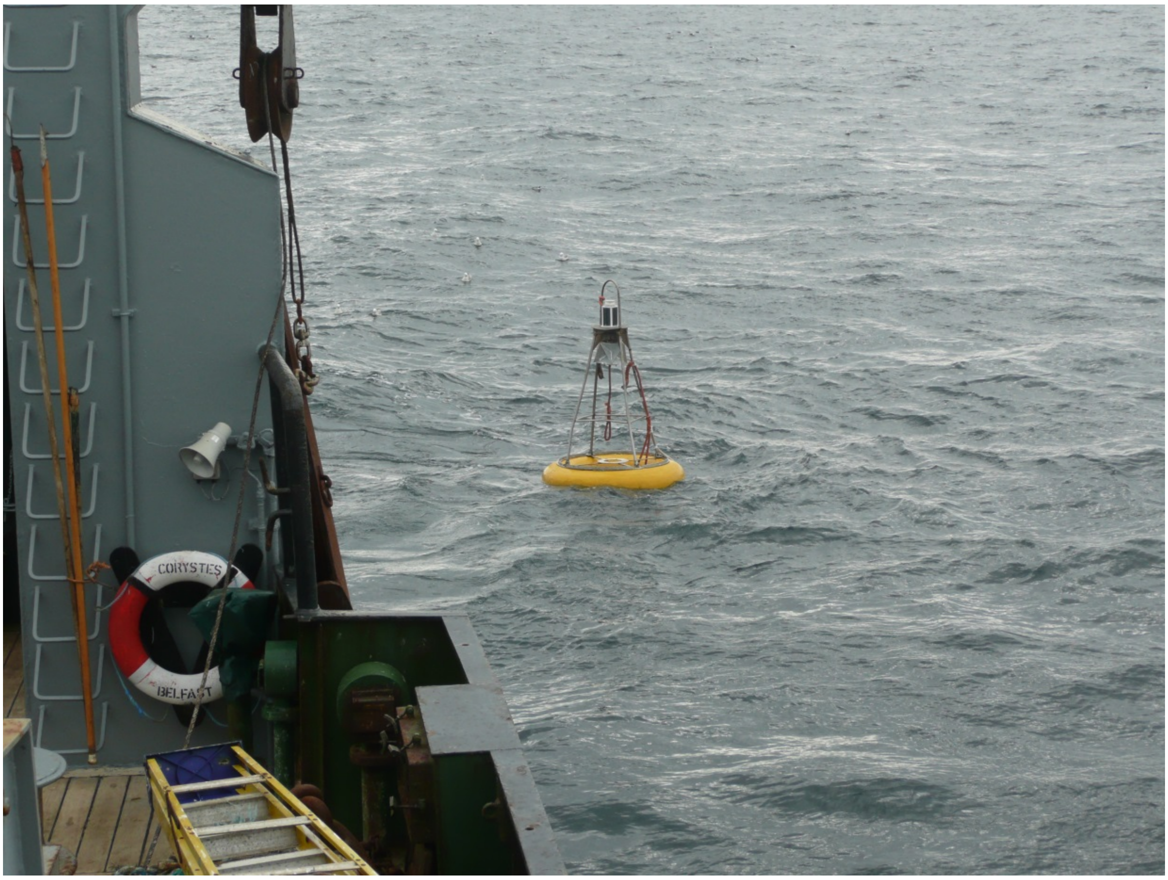


Fig. B19. Possible alternative surface expression for a lander frame L shaped mooring

Appendix C – Mooring to lander frame coupling and operational procedures

This appendix provides a more detailed review of the mooring setup and ground line routing for NOCL lander frame as used during the UK-SSB programme of benthic research cruises during 2015. Research cruises DY021 from 1st to 26th March, DY030 from 4th to 25th May and DY034 from 6th August to 2nd September all used an L shaped mooring as the primary mechanism to deploy and recover the miniSTABLE lander frame. The configuration of the mooring with respect to the lander frame was considered critical to achieving the successful operation of the highly sensitive scientific sensors and systems that were used.

The intention during the lander frame deployments was to keep the mooring ground line carefully routed along the upper part of the frame. The arrangement used was selected to keep any ground line movements away from sensitive instrumentation during the frame deployment. It was equally important to discourage any slack in the ground line from accumulating by or underneath the frame, to avoid disturbance of sensitive scientific measurements or possible damage to fragile instrumentation. A further concern with a steel cable on or close to the lander frame was that, as this line was tensioned to recover the frame, entanglement or possibly whiplash could occur that may damage sensitive scientific instrumentation. A steel cable if not insulated, should it come into contact with the aluminium lander frame, could also result in the onset of galvanic corrosion during a lander frame deployment. If left unchecked then galvanic corrosion could compromise the integrity of the mooring line, couplings or lander frame. Initially for the first deployment during DY021 in March 2015 a series of small plastic breakable fasteners were used. The requirement was to encourage the steel ground line to follow a preferred route from the coupling at the top of the frame to one of the frame legs, as shown in fig. C1.

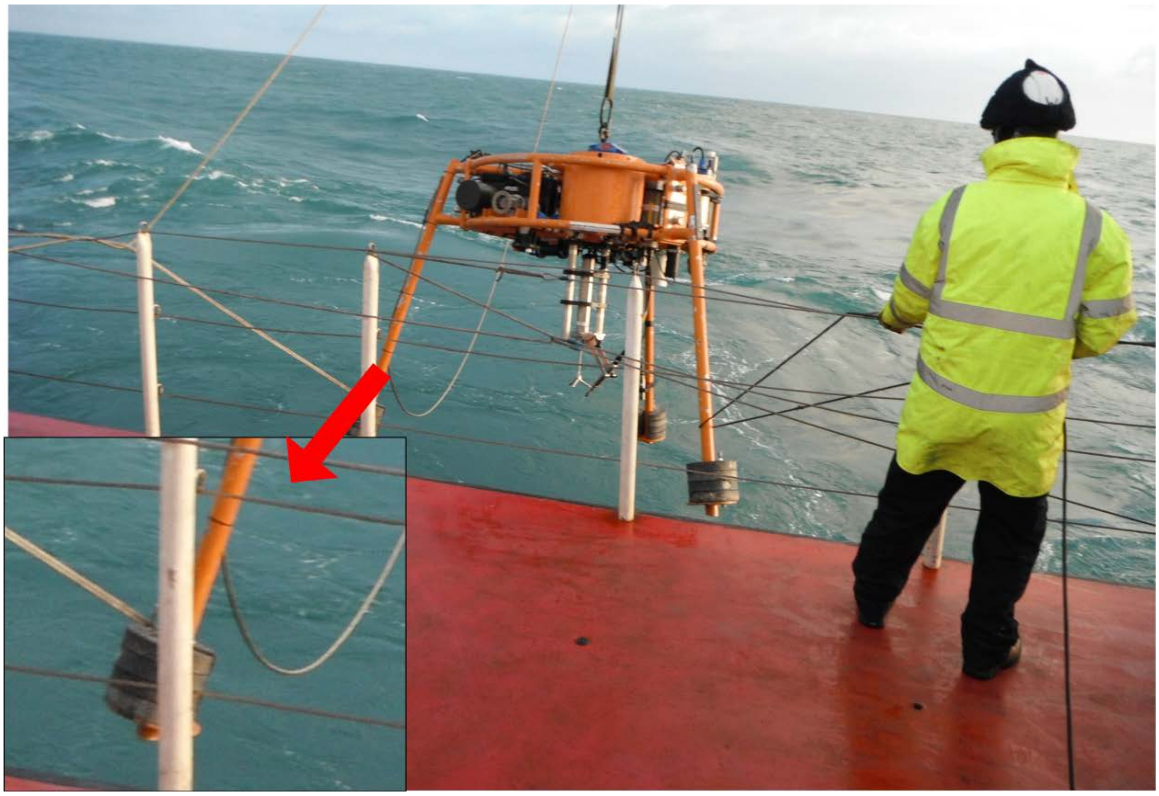


Fig. C1. A temporary plastic fasteners were used to keep the ground line cable in position along a preferred route from the central lifting coupling along the lander frame and down one of the frame legs

During the first DY021 cruise based lander frame deployment the ground line was accidentally and momentarily tensioned leading to breaking of the fastening along the frame leg as shown in fig. C2. The uncontrolled slack and routing of the ground line now presented the risk of movement, and possible whiplash damage to sensitive scientific equipment mounted on the lander frame, during tensioning as part of the recovery operations at the end of the deployment. This risk could be exacerbated if there any slack in the ground line had accumulated either on or close to the lander frame when it was initially deployed.

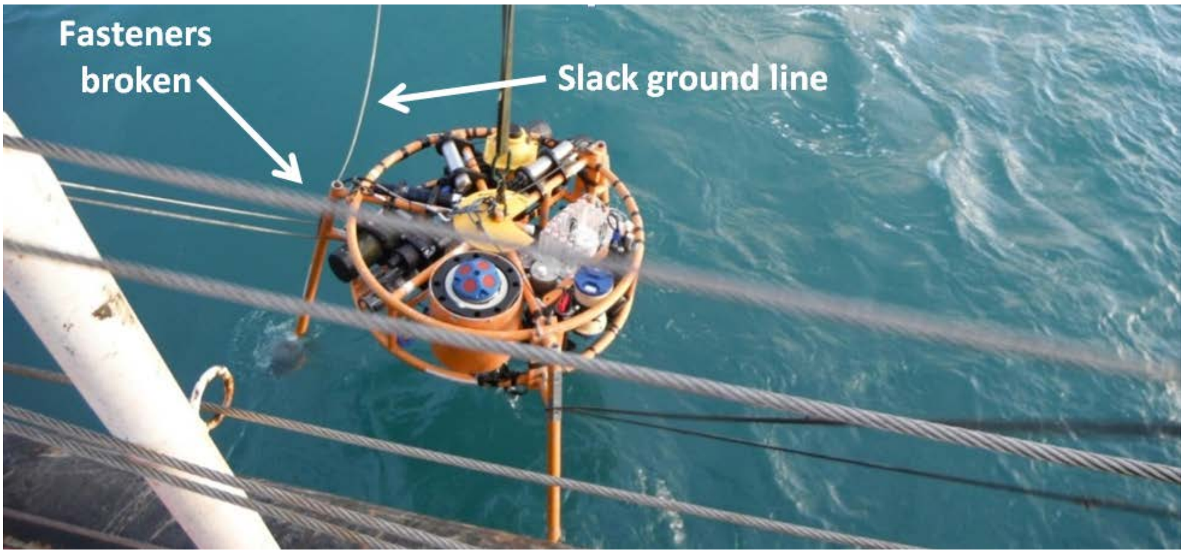


Fig. C2. The plastic fastenings of the ground line along one of the frame legs was broken

To avoid this problem a more robust albeit crude method of fastening the ground line cable was for the later DY030 and DY034 research cruises. This comprised of a combination of breakable plastic fasteners and adhesive tape, as shown in figs C3 and C4.

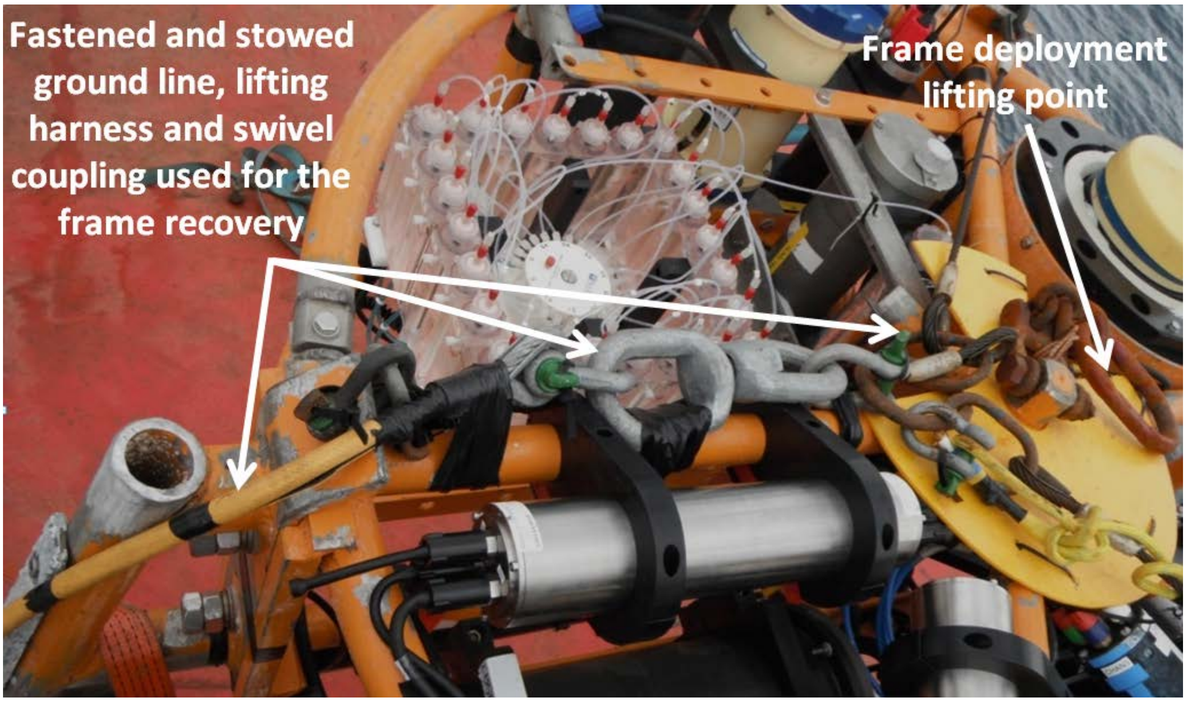


Fig. C3. Ground line fastening along the upper part of the frame, as used during DY034

A triple lifting harness with a central link using shackled steel cables to each frame leg was used to lift the lander frame from the seabed during a post-deployment recovery. The position of the lifting harness on the upper part of the frame needed to be carefully controlled as shown in fig. C3. In addition to this the relatively heavy, bulky galvanised swivel coupling that was used for the ground line connection to avoid line twisting, needed to be carefully routed and temporarily stowed for the deployment. This was necessary to avoid damage to sensitive equipment such as the McLane RAS100 water sampler connecting tubes that were in close proximity to the mooring line route.

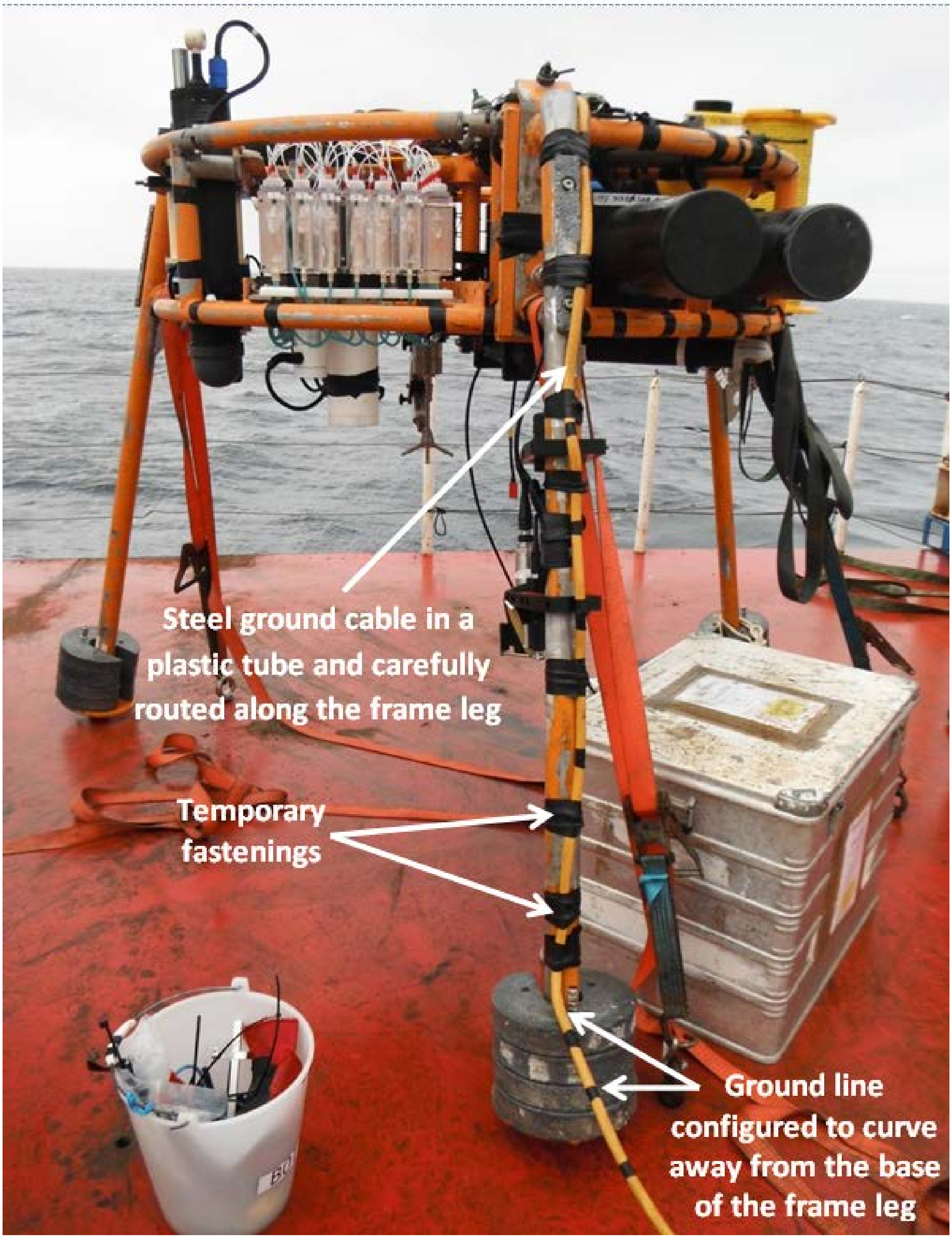


Fig. C4. A yellow plastic tube used for ground line steel cable insulation as shown in the picture. The fastening points along one of the frame legs and the curvature of the ground line away from the frame, as used during the DY034 research cruise, can be seen.

The layout of the triple harness for the lander frame recovery and the central articulated red link for frame deployment was carefully chosen. Unrestricted access to the lander frame alternative and central lifting point, as indicated in fig C3, was required to allow the required flexible lifting strop based deployment via an inline acoustic release to operate correctly. As described previously, and following a controlled, slow decent of the lander to the seabed, one side of the strop was released using an inline acoustic. The lifting strop was slowly and vertically winched away from the central lifting point on the frame for the first few metres of the deployment line recovery. This was to reduce the chances of the strop snagging during the release of the frame on the seabed and the subsequent recovery of the deployment line, acoustic release and lander lifting strop. The plastic insulating tube that was fitted around the first 4m of the steel ground line cable for the L shaped lander mooring is shown in the photograph in fig. C4. This was installed to avoid galvanic corrosion occurring, if the steel ground line cable comes into contact with the aluminium lander frame while the frame was deployed underwater. The use of a plastic tube also tended to stiffen the ground line. This promoted curving of the line along the frame and away from the leg and underside of the frame. The plastic cable tie and adhesive tape based temporary couplings were arranged to control the ground line position along the outer part of the frame. A specific route was used along the upper frame and then down towards the base of one of the frame legs. The fastenings were chosen with the intention of the couplings breaking as the ground line was tensioned and the full frame load was taken by the line in order to recover the frame at the end of a deployment. The requirement was also for the temporary couplings of the ground line to break in a controlled and progressive sequence. The preferred sequence was starting from the frame leg, close to one of the lead ballast sections at the base of the frame, and then upwards and along the frame towards the central lifting point. The use of a more robust temporary fastening of the ground line to the lander frame also allowed control of the frame heading and orientation during the deployments, as shown in the photographs in figures C5 and C6.

Fig. C5. Use of the ground line fastened to one of the frame legs to control the lander frame position and dampen any frame oscillations during a DY034 research cruise deployment

A limited amount of tension could be applied to the more robust temporary fastenings that were used close to the base of one of the frame legs, as per figs C5 and C6. This helped to control the frame position and dampen any frame movements during the initial phases of a deployment as the frame was lowered. Careful control of the lander deployment sequence such as this was used to reduce the chances of damage to the fragile glass envelope based dissolved oxygen sensor that was positioned below the upper central assembly on the lander frame.

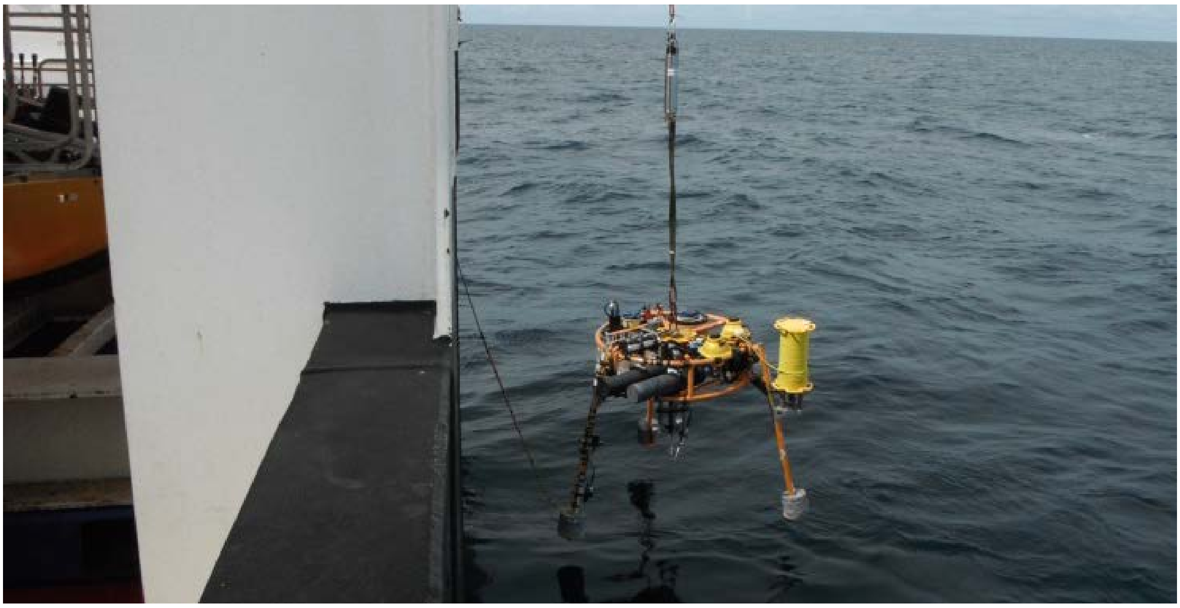


Fig. C6. Limited ground line tension was used to control the frame alignment during the critical initial phases of a deployment during DY034.

The photograph in fig C7 shows an example of the triple cable to frame lifting link harness usage for a lander frame recovery during the DY034 research cruise. The swivel coupling to avoid twisting of the ground line during the frame recovery had fully deployed without damage to any of the lander instrumentation.

Fig. C7. Lander frame recovery using the triple line frame lifting harness during DY034

While the use of an L shaped mooring is a robust and reliable mechanism to deploy and recover a lander frame, a potential drawback is the lack of control of the tension and angle of the ground line as the frame was recovered. The lander frame tended to be tilted, tipped over and then possibly dragged when the ground line was winched from the stern of RRS Discovery to recover the frame. A possible side effect of using a stronger, breakable ground line tie off was that frame tipping may occur during recovery before all of the temporary fastenings have broken. Sediment deposits on the backup recovery spooler outer edge were observed after each of the lander frame recoveries during DY034, as per the example in the photograph in fig. C8.

Fig. C8. Sediment build up on the outer edge of the recovery spooler indicating the frame tipping had occurred during the lander frame recovery

The backup recovery spool was on the opposite side of the frame to the ground line, indicating that the frame had possibly been tipped over during the recovery. This was despite the best efforts of the RRS Discovery crew, first to align the ship, and then to attempt to haul the lander frame with the ground line positioned vertically and as close as possible to the lander frame deployment position on the seabed.

A mechanism for attaching a ground line with electrical isolation and to a specific breaking strain was not available for the NOCL lander deployments as part of the RRS Discovery based UK-SSB research cruise programme. This perhaps could have mitigated some of risk of tipping the lander frame during the early phases of a recovery. It is important to note that frame tipping had occurred with previous RRS Discovery cruise based NOCL lander frame recoveries using the same L shaped mooring design, when a weaker or broken ground line fastening to the frame was used. It was therefore considered that possible parasitic and momentary frame tipping during a recovery was an acceptable side effect to achieve the desired and carefully controlled frame deployment procedure. A priority was the control of the ground line routing for the deployment and progressive separation of the ground line cable from the lander frame during the recovery. This was implemented to reduce the likelihood of damage to sensitive scientific instrumentation by undesired mooring ground line movements, tensioning and possible whiplash during recovery.

It is also important to highlight the fact that the fragile glass envelope based oxygen micro-sensor underneath the frame was not damaged during any of the DY034 deployments or recoveries. In addition to this, no significant damage was sustained by any of the NOCL lander scientific instrumentation. Subsequent analysis of the lander attitude sensor measurements revealed that the lander was upright during all four DY034 deployments. Momentary frame tipping only occurred as the frame was initially hauled from the seabed to the sea surface using the mooring at the end of a deployment.

Appendix D – Summary of the lander deployments for the UK-SSB programme

Between March 2014 and August 2015 ten deployments of the NOCL miniSTABLE lander were completed as part of the sequence of benthic survey cruises using RRS Discovery for the UK-SSB research programme. This appendix provides a review of the key features of each of the deployments. Table D1 provides a general overview of the deployments completed at each of the benthic survey sites.

Table. D1. NOCL benthic lander deployment summary

Survey site	Deployment number	Cruise, month and Year
Benthic A	1 of 2	DY021 March 2015[#]
	2 of 2	DY034 August 2015
Benthic G	1 of 4	DY008 March 2014
	2 of 4	DY021 March 2015
	3 of 4	DY030 May 2015*
	4 of 4	DY034 August 2015
Benthic H	1 of 1	DY034 August 2015
Benthic I	1 of 2	DY030 May 2015
	2 of 2	DY034 August 2015
Site 1	1 of 1	DY030 May 2015

[#] Eddy correlation sensor measurements were contaminated by the frame sinking ~50cm into the seabed.
* The lander was tipped on its side for the full deployment due to an initial mooring configuration problem.

Following the first deployment of the lander at the benthic A survey site during the DY021 research cruise, frame sinking into the fine scale low density sediment occurred to a depth of approximately 50cm. This prevented the eddy correlation velocity and dissolved oxygen sensors for operating correctly due to immersion in fine scale sediment. A review was then undertaken of the likely seabed consistency at each of the benthic survey sites. This was based upon preliminary results obtained from core sampling and sieve based analysis during the first benthic survey cruise in the UK-SSB project, DY008 in 2014. This allowed the likely seabed characteristics of a deployment site to be estimated. The height of eddy correlation sensors below the lander frame was then raised for subsequent deployments if lander frame sinking was likely to occur. An upgraded and modified mounting bracket system underneath the lander frame was used to achieve this. The elevation of the eddy correlation sensors was based upon the degree of sinking of the lander that was observed during the initial benthic A deployment. The anticipated relative sediment density and consistency at a particular alternative deployment site such as benthic H and I was taken into consideration. This technique of raising the eddy correlation sensors to counteract the anticipated frame sinking at the benthic A, H and I sites, where lower density seabed based sediment was expected, was demonstrated to provide a solution to compensate for the frame sinking problem.

Several scientific measuring systems on the lander frame included attitude sensors. Acoustic ranging of the distance of the seabed from the frame was possible with multiple downward facing sensors such as the Aquadopp, Aquascat and 3D Ripple Profiler. This allowed the orientation of the frame and the degree of frame sinking to be measured throughout a deployment. Contamination of the eddy correlation dissolved oxygen and velocity measurement sensors by sinking into the seabed was avoided for subsequent deployments at the benthic A, H and I survey sites by raising the sensor height when required. The eddy correlation sensors below the lander frame were subsequently maintained at a satisfactory height above the seabed after the lander had settled into the sediment on the seabed. For each lander deployment, irrespective of when significant lander sinking into the seabed did occur, the attitude of the frame was measured as close to the desired vertical orientation. When significant sinking of the lander into fine scale sediment of several cm or more did occur then this tended to be during the very early phases of a deployment and within an hour of the physical deployment of the lander on the seabed. The exception to this was the deployment at benthic G during the DY030 research cruise in May 2015. The benthic lander frame was tipped on its side throughout the deployment. This occurred due to a problem with the mooring deployment procedure. It was not possible to confirm the orientation of the lander frame until after the recovery when the measurements recorded by the scientific measuring system could be retrieved.

Scheduling of experiments and time constraints during the DY030 cruise dictated that an alternative study area called Site 1 at a GPS location of 49° 23.8785’N, 8° 36.5000’W was used for the third lander deployment. This study location had similar seabed sediment properties to the benthic G survey site, although the water depth was approximately 50m deeper than the typically 100-110m water depth at the benthic A, G, H and I survey sites.

In general the scientific measuring systems attached to the lander operated correctly during each of the deployments. Occasionally instrumentation setup problems, instrumentation faults or battery problems were experienced. A more detailed review of each of the lander deployments is provided in the following tables D2 to D11. A very brief description of the data return from each of the measuring systems and the water sampler is provided, in addition to a basic overview of the key features of that particular deployment. The times specified are in GMT.

D1 - Summary of the recovered data sets from the DY008 research cruise

Only one lander deployment was attempted during DY008 due to a problem with a commercial spooler system that was used as the primary method to recover the lander frame.

Table. D2. DY008 Deployment 1 of 1

Benthic G survey site deployment from 12:54 on 13/03/14 to 09:09 on 07/04/15. The nominal water depth was 99m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Images not recorded due to an instrument battery problem
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data to each instrument’s associated battery or internal memory store limits, with the exception of the LISST HOLO.

D2 - Summary of the recovered data sets from the DY021 research cruise

This was the first research cruise in the UK-SSB programme to use an L shaped mooring as the primary mechanism for deployment and recovery of the lander frame. The mooring was broken during one of the attempts to recover the lander frame, leading to a longer than planned second deployment. A trawl of the ground line from RRS Discovery was necessary to recover the lander via the ground line to seabed anchor connection. A backup recovery system was not available for the DY021 research cruse.

Table. D3. DY021 Deployment 1 of 2

Benthic A survey site deployment from 07:55 on 06/03/15 to 14:49 on 08/03/15. The nominal water depth was 108m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return – oxygen and velocity measurements contaminated
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	This deployment was the first use of an L shaped mooring to deploy and recover the lander, which was successful. All of the instruments recorded data to each instrument’s associated battery or internal memory store limits. The lander frame experienced sinking at the benthic A survey site, leading to contaminated oxygen probe and velocity measurements from the eddy correlation system.

Table. D4. DY021 Deployment 2 of 2

Benthic G deployment from 18:45 on 13/03/15 to 16:48 on 20/03/15. The nominal water depth was 105m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Only ~1 day of data was recovered due to an instrument problem
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Only 1 day of data was recorded due to an instrument battery problem
Comments	All of the instruments recorded data subject to each instrument’s associated battery or internal memory store limits, with the exception of the 3D ripple profiler and Aquadopp. A broken mooring during the first recovery attempt resulted in a ground line trawl being used to recover the lander.

D3 - Summary of the recovered data sets from the DY030 research cruise

This was the second research cruise to use an L shaped mooring as the primary mechanism for deployment and recovery of the lander frame. A backup recovery line and spool was implemented for this cruise. Unfortunately, a mooring related problem led to the lander frame being tipped onto its side during the first deployment. The mooring was broken after the second deployment leading to a longer than planned frame deployment. The backup recovery system comprising of a releasable float and coil of neutrally buoyant high strength line was used to retrieve the lander from the second deployment. The broken mooring was subsequently replaced with spare parts that had been procured to allow a third deployment of the lander to be undertaken during DY030.

Table. D5. DY030 Deployment 1 of 3

Benthic G survey site deployment from 06:47 on 08/05/15 to 07:35 on 13/05/15. The nominal water depth was 101m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return - frame orientation problems affected this measurement
Eddy Correlation	Full data return - frame orientation problems affected this measurement
3D Ripple Profiler	Full data return - frame orientation problems affected this measurement
LISST 100X	Full data return - frame orientation problems affected this measurement
LISST HOLO	Full data return - frame orientation problems affected this measurement
FSI (CTD) + SUNA	Full data return - frame orientation problems affected this measurement
AQUASCAT 1000	Full data return - frame orientation problems affected this measurement
NORTEK AQUADOP	Full data return - frame orientation problems affected this measurement
Comments	All of the instruments recorded data subject to the battery or internal memory store limits. An initial mooring setup and configuration problem resulted in the lander being tipped on its side for the duration of this deployment.

Table. D6. DY030 Deployment 2 of 3

Benthic I survey site deployment from 05:52 on 17/05/15 to 10:30 on 20/05/15. The nominal water depth was 110m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data subject to the battery or internal memory store limits. The mooring was broken during the first recovery attempt and the backup recovery system was used to recover the lander.

Table. D7. DY030 Deployment 3 of 3

Site 1 deployment from 13:42 on 21/05/15 to 09:23 on 23/05/15. The nominal water depth was 146m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return – lower sample rate inadvertently used
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data subject to the battery or internal memory store limits. A reduced measurement sample rate was inadvertently used for the eddy correlation system that resulted in a lower than planned measurement resolution. Cruise scheduling constraints dictated that the third lander deployment occurred at an alternative study site that was similar in seabed based properties to the benthic G survey site.

D4 - Summary of the recovered data sets from the DY034 research cruise

This was the third research cruise to use an L shaped mooring as the primary mechanism for deployment and recovery of the lander frame. A backup recovery line and spool was implemented for this cruise. All four deployments and recoveries using the L shaped mooring were completed successfully during this cruise.

Table. D8. DY034 Deployment 1 of 4

Benthic G survey site deployment from 14:02 on 08/08/15 to 14:00 on 10/08/15. The nominal water depth was 99m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Images not recorded due to an instrument configuration problem
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data to the battery or internal memory store limits, with the exception of the LISST HOLO that was incorrectly configured.

Table. D9. DY034 Deployment 2 of 4

Benthic A survey site deployment from 11:14 on 13/08/15 to 19:15 on 15/08/15. The nominal water depth was 107m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	No water samples were collected due to a fault with the water sampler
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data to the battery or internal memory store limits, with the exception of the McLane RAS100 water sampler that did not operate correctly.

Table. D10. DY034 Deployment 3 of 4

Benthic H survey site deployment from 08:30 on 19/08/15 to 08:00 on 21/08/15. The nominal water depth was 108m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data to the battery or internal memory store limits associated with a particular instrument.

Table. D11. DY034 Deployment 4 of 4

Benthic I survey site deployment from 16:10 on 24/08/15 to 07:00 on 30/08/15. The nominal water depth was 109m.	
Instrument	**Preliminary data quality check**
McLane RAS 100	Full water sample return and inline particulate filter recovery
1200KHz RDI ADCP	Full data return
Eddy Correlation	Full data return
3D Ripple Profiler	Full data return
LISST 100X	Full data return
LISST HOLO	Full data return
FSI (CTD) + SUNA	Full data return
AQUASCAT 1000	Full data return
NORTEK AQUADOP	Full data return
Comments	All of the instruments recorded data to the battery or internal memory store limits associated with a particular instrument.