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RRS *Discovery* Cruise D381B OSMOSIS Project
Turbulence glider operations report
September 2012

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ABSTRACT

This report provides a brief overview of the Teledyne Webb Research Slocum Electric Glider operations during the RRS *Discovery* based D381B research cruise. This cruise was commissioned to support the Ocean Surface Mixing, Ocean Sub-mesoscale Interaction Study (OSMOSIS) research project. The glider used had a specialist turbulence probe attached that was supplied by Rockland Scientific International. This system was used to provide millimetre scale resolution of changes to the physical properties of the water column such as temperature, conductivity and shear force. The glider was used in conjunction with more established turbulence measurements operating from a research vessel to establish comparative measurements during key surveys within the cruise schedule. The survey work occurred above the Porcupine Abyssal Plane area of the Celtic Sea at a nominal GPS location of 48º 41.340’N, 16º 11.400’W and a nominal water depth of approximately 4800 metres.

KEYWORDS:

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Terms and Definitions

Turbulence Glider	A 200 metre depth rated generation 1 or G1 type Slocum Electric Glider. This is small AUV that is designed for oceanographic survey work. The glider is manufactured by Teledyne Webb Research, America. The turbulence glider has a Seabird Electronics non pumped CTD sensor and a Rockland Scientific International micro-Rider turbulence sensor installed.
OSMOSIS	Ocean Surface Mixing, Ocean Sub-mesoscale Interaction Study. This research project is led by Reading University and the partners are Southampton, Oxford, Bangor Universities, the University of East Anglia, the National Oceanography Centre, the Scottish Association for Marine Science and the UK Met Office.
FreeWave	Wireless short range radio link based glider communications
Iridium	Wireless data transfer based upon the Iridium low earth orbit satellite constellation.
Argos	Wireless data transfer based upon the Argos low earth orbit satellite constellation.

Abbreviations

NOCL	National Oceanography Centre, Liverpool, UK
AUV	Autonomous Underwater Vehicle
TWR	Teledyne Webb Research
RSI	Rockland Scientific International
MSS	A turbulence sensor manufactured by Sea & Sun Technology GmbH, Germany
CTD	Conductivity, temperature and depth sensor
ADCP	Acoustic Doppler Current Profiler
ODAS Buoy	A sea surface based buoy that is provided by the UK Met Office that has a standard metrological instrumentation package installed.
PAP	Celtic Sea Porcupine Abyssal Plane
GPS	Global Positioning System
GMT	Greenwich Mean Time
EMC	Electromagnetic compatibility
RHIB	Rigid Hull Inflatable Boat
IPA	Isopropyl Alcohol de-greaser

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1. OSMOSIS Project Turbulence Measurement Overview and Objectives

This document provides an overview of the turbulence glider operations that occurred during the RRS *Discovery* based D381B research cruise for the OSMOSIS project. RRS *Discovery* departed from Falmouth, UK on Friday 14th September 2012 and returned to Southampton, UK on Wednesday 3rd October 2012.

The general scientific objective of the Celtic Sea PAP survey was to study atmosphere/ocean heat exchange. The goal of the PAP MSS and turbulence glider study is to measure and understand the turbulent processes in the upper part of the water column, where the properties of which determine the atmosphere/ocean heat exchange. This work complimented the additional mooring and ship based measurements of the physical properties of the water column such as changes in currents, temperature, salinity, mixing and stratification. Measurement and detailed understanding of these processes will help to provide information to validate predictive models to assist with objectives such as improved weather forecasting. Two key sets of processes are in operation at the survey site. Firstly the wind stress and wave driven shallower water effects include Langmuir circulation. This occurs when a particular kind of wind blowing steadily over the sea surface causes a series of shallow water counter rotating vortices to form close to the sea surface, usually at maximum depths of up to approximately 20 metres although the effect of this can extend further. In addition to this the deeper water mixed layer is also affected by mean ocean current flow. This ocean current flow can be established for periods of time from hours to months in duration. The ship based MSS survey measured the dissipation of turbulent kinetic energy in the upper 100-200m of the water column close to the PAP mooring array. In the same general area, typically several kilometres away, an underwater glider was deployed and maintained on station. This glider was used to provide a second set of turbulence measurements using a specialised sensor. These measurements were undertaken along the full length of the water column to a nominal depth of 100m, with typically three dive and climb cycles of turbulence measurements occurring per hour. The MSS and glider turbulence measurements should provide detailed fine scale turbulent kinetic energy dissipation information for the upper water column. Comparison of the MSS and glider data sets should also provide the extent to which ship introduced turbulence is contaminating the MSS data. Both sets of measurement systems have the capability of millimetre scale resolution due to the turbulence sensor sensitivities and data sampling rates used. Outside of the MSS profiling intervals during the D381B research cruise the turbulence glider continued to record a continuous set of scientific measurements in close proximity to the PAP moorings.

The location of the OSMOSIS moorings is shown in Fig. 1. The mooring arrangement consists of deep water moorings and sub surface buoys to position a series of instrumentation arrays to measure the upper part of the water column. The measuring range would be typically the upper 50-100 metres of the water column. The instrumentation comprises of CTDs, temperature logger arrays and ADCPs. In addition to water velocity measurements, four of the ADCPs in the inner part of the mooring array are configured to measure turbulence. To the north of the moorings array a standard ODAS metrological buoy was deployed. The general requirement of the moorings is to provide sub-meter scale measurements of the upper part of the water column. This provides a time series measurement of the re-stratification of the water surface layer to support physical oceanographic process studies.

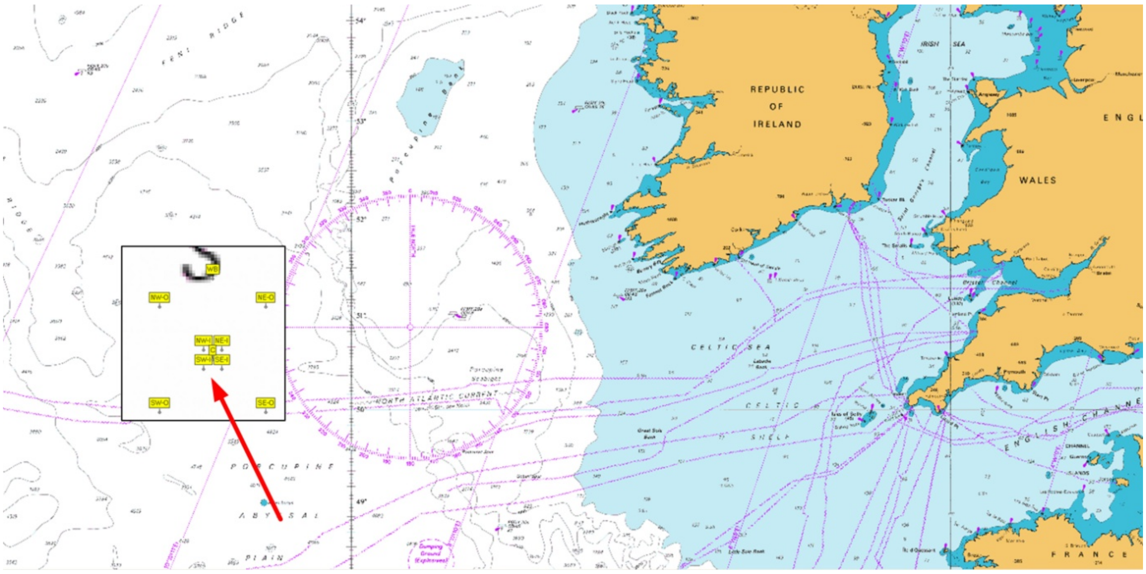


Fig. 1. Survey Area and Moorings Array Above the Celtic Sea Porcupine Abyssal Plane (PAP)

The turbulence glider was operating within several kilometres of the OSMOSIS moorings array. The moorings had a nominal centre cluster of sensors at a GPS location of 48° 41.340'N, 16° 11.400'W.

Before the glider deployment and mobilisation for the D381B cruise occurred the electronic compass in the glider was recalibrated after a new set of batteries were installed. Appendix A provides some basic details of the compass calibration procedure and results. In addition to this a test facility in the University of Liverpool Hydraulics lab was used to ballast the glider. To assess the ballasting of the glider a portable water tank was used on RRS *Discovery* to test the glider in near surface sea water close to the intended deployment location. Further details of the ballasting tests and configuration can be found in appendix B. A labelled diagram of the turbulence glider is shown in Fig. 2. The turbulence probe is the black tube mounted above the front hull of the glider. A custom guard has been fitted close to the delicate turbulence sensor probes. This is designed to provide some level of protection of the probes from damage, while not affecting the turbulence measurements too adversely. The protection of the probes by the guard is particularly useful during glider deployment and recovery operations, where impacts with the glider probes are likely to occur. During the deployment of the glider the high volume of data generated by the micro-Rider turbulence probe is stored internally inside the sensor. The glider provides power to the turbulence sensor and a signal to turn on or off turbulence data recording. The mounting of a sensor such as this on the turbulence glider means that great care must be taken to correctly ballast and configure the vehicle for a deployment. In advance of the deployment in the wet lab of RRS *Discovery* the glider hull seal o-rings and real vacuum seal port o-rings were replaced with new seals. All of the hull sealing faces were cleaned with IPA and re-greased during this process. A test was used to check that the glider can maintain the required internal vacuum pressure overnight. This provided a basic check of the glider hull seal integrity. In addition to this the fore and aft hull mounting sacrificial zinc anodes on the glider and the zinc anodes on the micro-Rider sensor were replaced with new units before the glider deployment.

Prior to the deployment of the turbulence glider all of the glider communication systems such as Iridium, FreeWave, Argos and the GPS receiver were tested on the starboard outer deck of the ship, where a reasonably clear view of the sky is possible for satellite communications tests. An 'on_bench' simulation was run in the glider overnight of the intended PAP turbulence survey glider mission. For this test the GPS and pressure measurements are simulated and the glider operates all of its actuators as it would do during a deployment. This confirmed that the glider, glider CTD and micro-Rider turbulence sensors were correctly operating under the direction of the planned survey mission configuration.

2. Glider Deployment Operations

Following the completion of the glider testing in the wet lab the glider was transported to the starboard deck of RRS *Discovery*. After final communications checks were completed the glider was lifted using a ship based crane and dual strop arrangement. Stay lines were used to keep the strops in tension around the glider fore and aft hull sections prior to deployment. The stay lines also provided a mechanism to stop the glider moving excessively due to the ship's motion. One side of the strops supporting the glider were connected to a quick release hook.

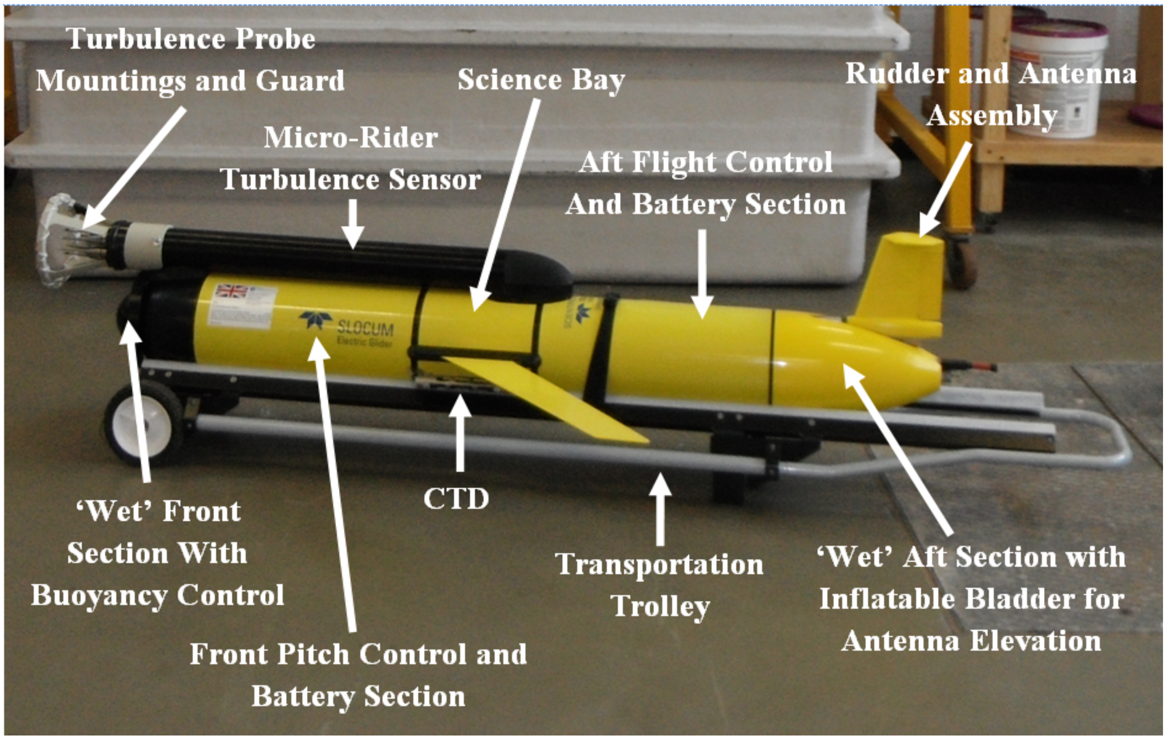
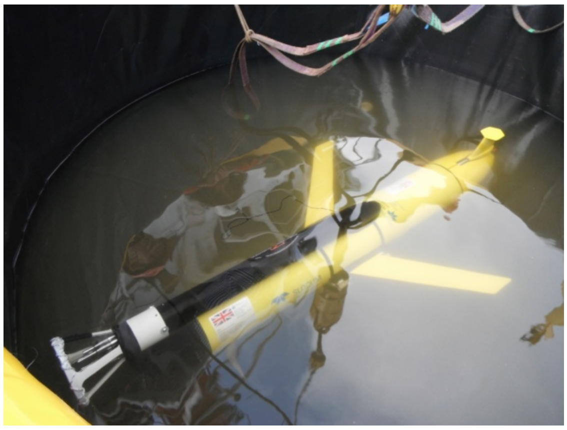


Fig. 2. Turbulence Glider Key Features

A safety pin and pull line was installed to prevent a premature release of the hook from occurring. This safety pin was removed from the release hook once the crane had positioned the glider over the side of the ship. As the glider was lowered to the sea surface the stay lines were then removed. The turbulence glider was deployed at a GPS location of 48° 46.731'N, 16° 22.816'W on Monday 17th September at 19:14 GMT at a water depth of approximately 4800 metres. The selected deployment location was approximately 14km to the west of the wave rider buoy at the northern part of the OSMOSIS moorings at the PAP survey site. A sequence of pictures that illustrate the glider deployment operations are shown in Fig. 3.

Once the glider was buoyant at the sea surface the release hook was then operated and the crane lifted the strops away from the glider to complete the deployment. A sea surface swell occurred during the glider operations that caused the deployed glider to move vertically on the sea surface relative to the ship. Before the crane lifting arm could be retracted the release hook impacted with the rear plastic cowling over the glider air bladder and below the tail section. No damage was evident to the cowling although this does illustrate the potential risk of using this type of deployment mechanism in anything other than a flat calm sea state. Two long fending off poles were on standby to prevent the glider from straying too close to the outer hull of RRS *Discovery* during the early phases of the deployment. When the glider was approximately 300m to 500m from the ship the pre deployment glider dive testing operations commenced. These tests were then undertaken using FreeWave wireless communications to the glider from an antenna mounted on the ship at an elevated position close to the CTD winch.

a Glider preparation in the wet lab of RRS *Discovery*



b A portable tank was used to test the turbulence glider ballasting with near surface seawater from the PAP survey site prior to deploying the glider.

c Lowering of the glider towards the sea surface

d Glider deployment. The sea surface swell is evident in this picture

Fig. 3. Turbulence Glider Preparation and Deployment

These operations involved checking the status of the vehicle, performing incremental test dives to 3 metres, and then 50 metres. After each test dive the recorded glider data was downloaded and plotted to assess the vehicle status and check for problems such as seawater ingress. The dive profile was also trimmed by adjusting the position of the pitch control battery pack at the start of dives and climbs. After successfully completing a set of 50 metre profiling dives of 30 minutes in duration the recorded sensor data from the glider was downloaded to the ship and a series of checks were undertaken. No problems were evident and at 20:39 GMT the glider survey mission to 100m depth profiles with the glider CTD and turbulence sensor operating were initiated. This completed the glider deployment operations. Casts from the RRS *Discovery* based CTD carousel prior to and after the glider deployment were used to provide the required reference calibration readings for the glider CTD sensor calibration. The glider operation was then closely monitored using the ship's internet connection as and when possible. Standby pilots were available at NOC Liverpool during normal working hours. A satellite phone was used to liaise with shore based personnel regarding the turbulence glider status when the RRS *Discovery* internet connection was inoperative for significant periods of time.

3. Turbulence Glider Piloting

The turbulence glider was configured to only make adjustments to the buoyancy pump or pitch control forward battery position motor during dive to climb or climb to dive inflections. The normal settings that automatically adjust the forward pitch battery position to optimise the glider dive and climb angles for maximum propulsion are turned off. This is essential to minimise electrical and mechanical interference with the operation of the highly sensitive turbulence measurement sensors. Progressive adjustments are required to trim the glider pitch battery control parameters to the desired settings for turbulence profiling in a particular survey area. This is required because the vehicle attitude will be affected by the properties of and any variations in the water column. The early phases of piloting of the turbulence glider for the OSMOSIS project deployment involved adjusting the dive and climb angles to 35°. This represents a steeper angle than the optimal 26° normally used. The general intention was to sacrifice forward propulsion efficiency for steeper survey profile angles. This is required from a science perspective to use the turbulence sensor as close to vertical profiling as possible. If a dive and climb angle steeper than 35° is used it is estimated that this may cause problems with the operation of the glider attitude sensor. Therefore the selected profiling angle represents the closest reasonable value to the desired vertical turbulence profiling that can be reliably achieved with the glider. A sample depth profile from the OSMOSIS project turbulence glider deployment is shown in Fig. 4. This illustrates a symmetrical dive and climb profile at the required pitch angle.

The glider was diving to a depth of 100m and then inflecting towards the sea surface. An upper inflection point of 3 metres was used and suspected vehicle momentum resulted in an inflection closer than 3m when the glider approached the sea surface. This produced turbulence measurements along the full length of the dive and climb profile as required. During the deployment the glider was kept as close as possible to the moorings array, particularly when additional turbulence measurements were undertaken using a ship based vertical MSS profiler. The MSS profiling system consisted of a long cable attached to the profiling instrument with a small winch that was located at the stern of RRS *Discovery* to drive the cable. The winch was used to pay out the cable at rate that allows the MSS profiler to freefall through the water column to a typical depth of 150 metres while making turbulence measurements. At the same time the ship moved at a speed of approximately 0.5 knots repeatedly along a 5-8km long profiling transect that was to the north west of the glider survey area. The measurements from the MSS system were transferred to a signal conditioning and data recording system on the ship by the long power and data cable that is connected to the profiler through the winch system. The instrument is then returned to the surface using the winch to haul the cable and subsequently the profiler. This process repeats to generate the required measurements. A series of stations were then undertaken whereby the MSS system generated vertical turbulence profiles in close proximity to the turbulence glider. The intention was to generate two sets of independent turbulence measurements in the same general work area close to the moorings array. The use of a more established MSS vertical turbulence profiling system from the ship was intended to act as a reference for comparison to assess the performance of the glider turbulence sensors.

Fig. 4. Sample Glider Underwater Depth and Pitch Profile

With the glider located at least several kilometres away from the ship during MSS profiling a further aim of the experiments was to see if any of the MSS generated water column turbulence features are not evident in the glider generated turbulence data. This would provide some level of indication of how the ship based turbulence profiles are being disturbed by the actual motion or propulsion of the ship. When the glider was surfacing to transfer near real time data over iridium it was losing ground and being driven from west to east. For the first MSS profiler survey the glider was holding its position during the MSS profiling from Monday 17th to Wednesday 19th September. During the second MSS survey from Saturday 22nd to Sunday 23rd September to the north west of the PAP moorings, the turbulence glider had drifted to approximately 10-20km away from the MSS profiling. The third MSS survey occurred from Thursday 27th to Friday 28th September after the turbulence glider had been recovered. A diagram of the MSS survey locations is shown in Fig. 5.

During the turbulence glider deployment a strong west to east underwater current was evident. The glider was deployed approximately 14km to the west of the mooring array and the effect of this current was to drive the glider to the east. The plot of the reported glider positions for the glider deployment shown in Fig. 5 illustrates this. The large red crosses represent the locations of the OSMOSIS moorings in the PAP survey site. The moorings were positioned within a rectangle of approximately 14km in width and 17km in length, with a centre mooring at a GPS location of 48° 44.340'N, 16° 11.400'W. The green rectangles in Fig. 6 represent the reported glider positions and the effect of the water current and surface currents driving the glider to the west can be seen.

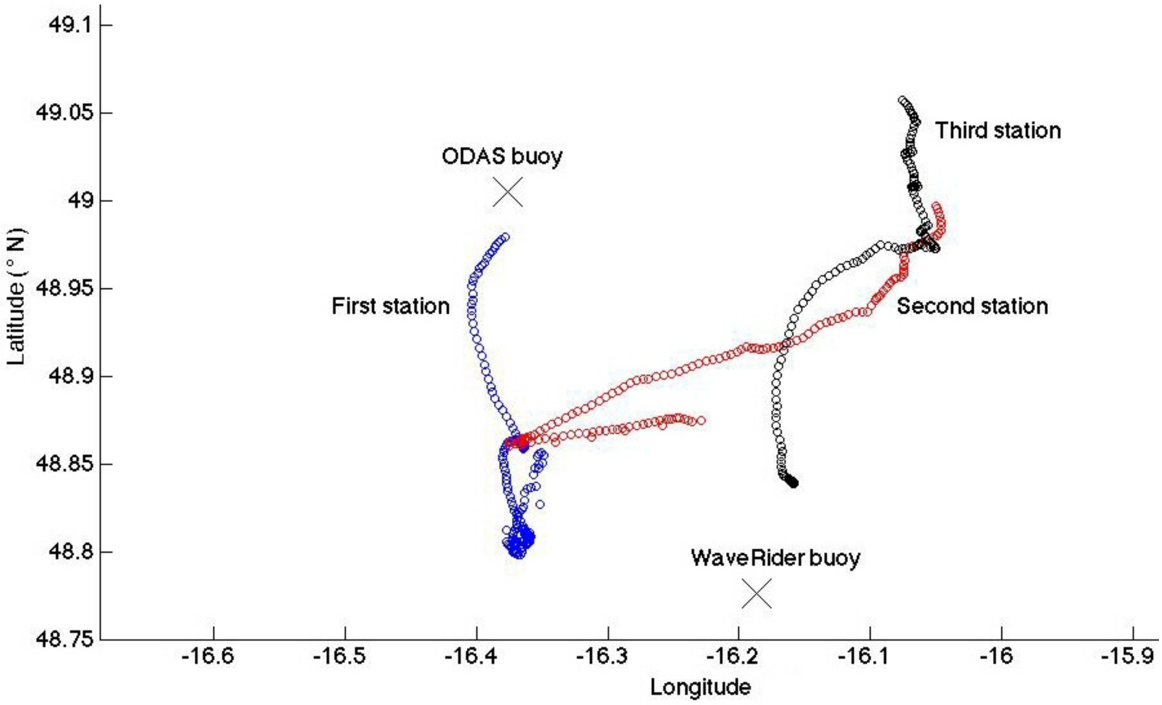


Fig. 5. D381B MSS Vertical Turbulence Profile Stations using RRS *Discovery*

(Plot courtesy of the universities of Bangor and Reading)

The actual piloting of the glider was undertaken aboard RRS *Discovery* using the ship's internet connection. This allowed communication with the glider using the iridium global satellite service. Basically, when the glider surfaces at timed intervals it tries to connect to the iridium satellite service and communicate with a server based in the NOC Liverpool laboratory that utilises a reliable high speed internet connection. The limited bandwidth, less reliable RRS *Discovery* internet service was used to monitor the glider progress. This was achieved by connecting to the NOC Liverpool glider server computer and monitoring the glider status. If required, data or configuration files could be transferred to or from the glider via the Liverpool server.

Throughout the second MSS vertical profiling sequence of transects the glider managed to sustain a position approximately 3km south east of the upper right mooring location shown in Fig. 6. The glider aborted its profiling mission several times, due to suspected intermittent EMC problems. These aborts were managed successfully by close monitoring of the glider performance. As and when required, pilot intervention occurred to deal with technical problems with the glider and resume the glider turbulence survey mission as soon as possible. Following the initial turbulence glider deployment, once the glider dive and climb profiles had been trimmed to the correct pitch angles, the mission configuration was altered. This was required to keep the glider underwater profiling for longer periods of time that were typically 3 hours in duration. Near real time data transfer using iridium of the glider flight and science sensor status data was been turned off. The glider simply surfaced, reported its GPS position and then resumed profiling. This limited the glider time on the sea surface and allowed the glider to maintain its position at the north east of the OSMOSIS PAP site mooring array, close to the moorings. If the ship's internet connection failed then a satellite phone was used during daytime working hours to contact NOC Liverpool to monitor the status of the glider. Standby pilots were also available at Liverpool to intervene in the turbulence glider piloting process throughout the turbulence glider deployment.

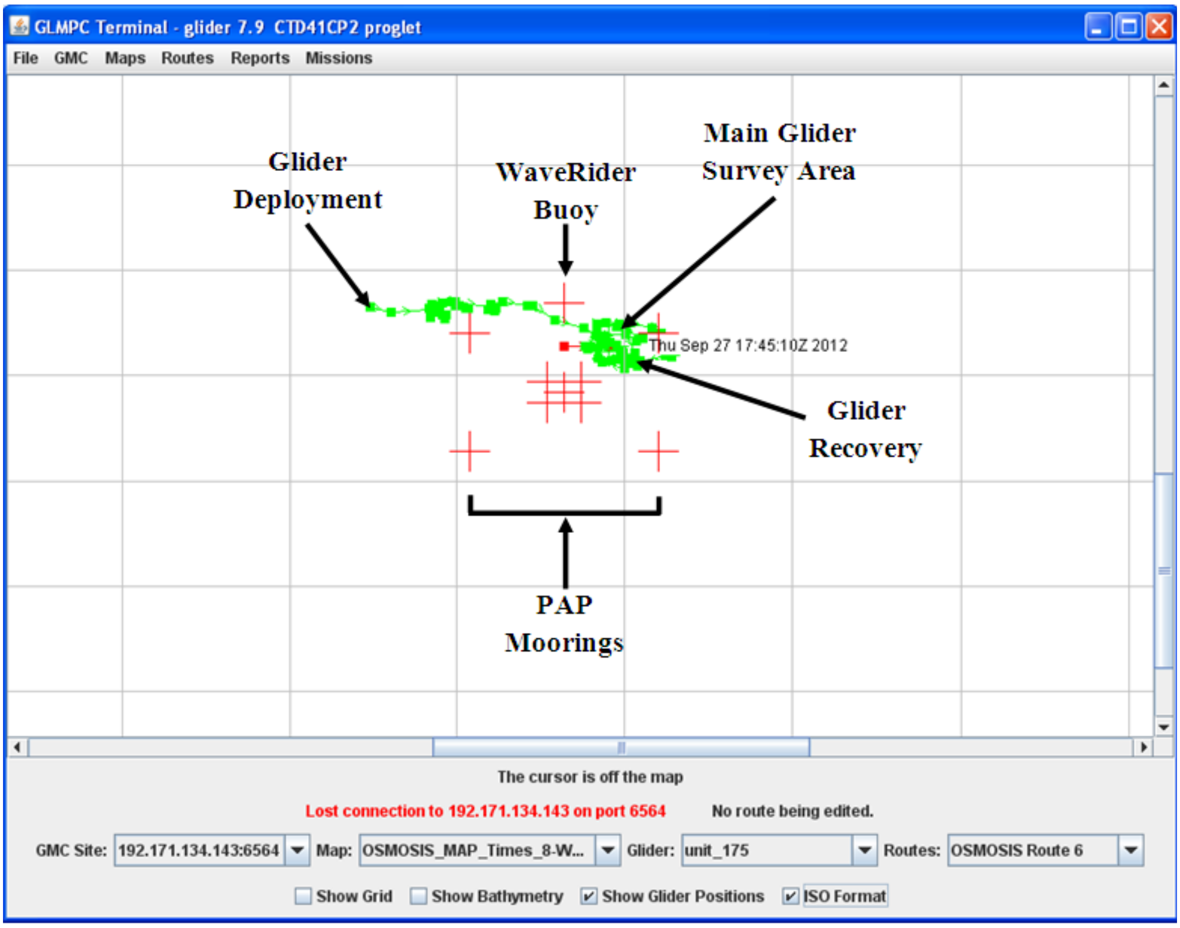
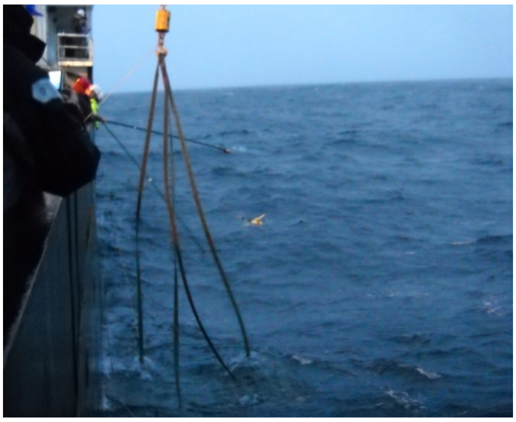


Fig. 6. Plot of the Reported Turbulence Glider Surfacing Positions Relative to the PAP Moorings

4. Turbulence Glider Recovery

During the cruise, a combination of bad weather and time constraints for the remainder of the scientific measurement programme resulted in an earlier than planned turbulence glider recovery attempt. The sea state was not ideal with a significant amount of swell and it was questionable if a recovery could or should be attempted. After consulting the deck crew and the senior crew in the bridge a decision was made to attempt a glider recovery. If the sea state was suitable and the current phase of mooring recoveries could be completed in time at least two hours before nightfall then a recovery attempt would be made. The mooring recoveries were completed at 17:10 GMT on Thursday 27th September and the glider was re-configured to 30 minute surfacing. At 17:25 GMT the glider was held on the surface and GPS updates from the glider were provided. Once the glider was within FreeWave wireless communications range the ship was manoeuvred into position with the glider approximately 100m from the front of the ship. After further consultation with the deck crew a recovery attempt was made. A sequence of photographs of the turbulence glider recovery operations are shown in Fig. 7. During the first recovery attempt the glider snagged one of the stay lines and then overshot the recovery net. Further attempts to drag the glider back to the net resulted in the loss of the port wing. RRS *Discovery* was re-aligned with the glider and during the second attempt the glider was manipulated onto the recovery net. The sea swell made this operation very difficult and precarious. long fending off poles were used to hold the glider in the net until the crane on the side of the ship could lift the glider clear of the water and back onto deck.

a Recovery net deployment



b Glider alignment for recovery

c Port wing lost after first recovery attempt

d Glider recovery. The sea swell and white cap can be seen in this picture just below the recovery net

e Turbulence probes clean and intact after the recovery

f Servicing of the recovered glider

Fig. 7. Turbulence Glider Recovery Operations

The glider was successfully recovered at 18:46 GMT on Thursday 27th September at a GPS location of 48° 43.274'N, 16° 07.023'W. After the recovery the glider was washed down with fresh water, dried and returned to the wet lab. An initial inspection revealed that there was no significant damage to the glider hull or main components although both wings were lost or damaged during the recovery. The micro-Rider was de-mounted and initial tests showed that the correct volume of data had been recorded. Preliminary tests also showed that the glider was operational and the internal vacuum had been sustained. This indicated that no significant damage or seawater ingress had occurred during the recovery process. The glider was then subsequently disassembled and the hull seals were cleaned and re-greased. A copy of the flight and science data recorded by the glider was then made. Following this a preliminary assessment of the glider science data was, undertaken as summarised in appendix C. Initial checks showed that the micro-Rider had recorded 7.27GB of science data and that all of the microstructure probes had been working correctly throughout the 10 day deployment. A preliminary evaluation of the glider CTD data showed that a problem with the science computer had caused the loss of approximately 1.5 days of CTD data. While this was disappointing, more than 8 days of precision CTD measurements had been recorded by the glider. The general feedback from the turbulence data scientists is that the micro-Rider turbulence data can be adequately calibrated with the existing data set to compensate for the interruption in the main glider CTD recording. This loss of glider CTD data occurred between day 8 and day 9 of the 10 day glider deployment (am on Wednesday 26th September to around midday on Thursday 27th September).

5. Summary

This report has provided an overview of what has been a highly successful deployment of the turbulence glider for the RRS *Discovery* based D381B scientific research cruise. The glider has generated 10 days of high resolution turbulence measurements. This data has been recorded within close proximity to the PAP moorings array in the Celtic Sea as required by the OSMOSIS project. Two MSS based vertical profiling surveys were also undertaken from RRS *Discovery* while the turbulence glider was deployed. At just over 8 days into the glider deployment a problem with the glider CTD measurements occurred and subsequently approximately 1.5 days of CTD data recordings were lost. During this time the micro-Rider turbulence probe continued to record high resolution measurements of temperature, micro-conductivity and shear at a rate of 512Hz. The result of this was that an impressive 7.27GB of raw micro-Rider scientific data was generated during the glider deployment. Some considerable effort will be required to post process and calibrate this data. It is envisaged that the calibration of the micro-Rider turbulence data with the exiting over 8 days of glider based precision CTD data will circumvent this problem. The calibrated micro-Rider turbulence probe data can then be used to provide millimetre resolution measurements of changes of temperature, salinity and shear forces for the entire deployment, particularly when the glider CTD was inoperative. The use of a specialist autonomous underwater glider in this way represents new an original contribution to oceanographic research.

The preliminary D381B research cruise specification for the glider deployment was that a three week turbulence survey would be required. To accommodate this, lithium primary expendable batteries were installed inside the glider. For the 10 day deployment of the glider approximately 25% of the stated maximum capacity of the batteries was used, in line with the endurance estimations for the glider in this configuration.

It was not feasible to perform an initial glider dive test with a tether and float to check the vehicle and ballasting setup in the early phases of the deployment. As an intermediate step before the risk of an un-tethered glider deployment a portable water tank was used to verify the glider setup and ballasting. In advance of the D381B cruise the installation of lithium primary batteries resulted in a mass reduction of the glider by approximately 5kg. A series of closely monitored ballasting tests had been undertaken with a tank of accurately mixed salt water in a laboratory environment at room temperature. An onboard check of the glider ballasting was considered necessary as the previous ballasting tests had been undertaken at a more elevated temperature than that expected during the deployment. Although the ship was moving the portable water tank used demonstrated that the glider was ballasted correctly for the near surface water conditions at the PAP survey site. In addition to this the glider was level and did not exhibit any excessive parasitic roll during the ballasting test. On the basis of these test results the decision was then made to deploy the glider. The portable test tank was only partially filled to approximately 20% due to concern that the motion of the ship could damage the tank due to the mass of water moving in the tank. As soon as the ballasting test was complete the tank was drained, washed out with fresh water and stowed. In advance of the ballasting test a series of comprehensive glider vehicle, communications and science sensor checks were also undertaken in the wet lab of RRS *Discovery* before the glider deployment. Following mobilisation of the glider and subsequent loading and unpacking on RRS *Discovery* the glider hull seals and rear vacuum port plus its o-ring seal were replaced. This was primarily aimed at addressing the possibility that the hull seal integrity could be affected by the glider transportation, loading and unpacking processes. An overnight test was also used to confirm that the glider could sustain the required internal vacuum pressure before any deployment operations commenced.

Other than the glider CTD measurement outage, the piloting of the glider worked well. Shortly after the deployment the pitch battery positions were trimmed during the beginning of the glider dives and climbs to provide the required 35° angles for turbulence profiling. The glider also managed to hold its position and stay at the required stations within the OSMOSIS project PAP moorings in the presence of a strong and relentless west to east underwater current. To keep the glider on station it was necessary to turn off the near real time data transfer from the glider to limit glider surfacing times. The result of this was it was more difficult to monitor the glider status and the science sensor operation. This subsequently meant that the identification of the glider CTD measurement problem was more difficult. Several sporadic glider mission aborts occurred during the deployment due to suspected iridium data modem EMC problems. These problems were managed effectively by glider pilot intervention that allowed the required scientific survey to be sustained. During outages of the RRS *Discovery* internet connection a satellite phone was used to call shore based backup pilots to monitor the status of the glider.

From the perspective of the actual glider deployment and recovery operations these proved both problematic and difficult, primarily due to a poor sea state. The dual strop and stay line deployment method, while supporting the glider safely, was precarious during the deployment. After the initial release of the glider the motion of RRS *Discovery* and the sea swell caused the glider position to move relative to the ship and the deployment crane. The metal release hook attached to the crane impacted with the glider before the deployment crane arm from the ship could be retracted. This problem was unavoidable due to the conditions that existed at the time. The initial observation was that a glancing blow to the rear air bladder plastic cowling had occurred. Fortunately, no obvious damage had been sustained and checks of the glider status showed no immediate problems with the glider. Post glider recovery checks subsequently confirmed this. After the impact with the glider occurred the decision was made to continue with the initial dive testing of the glider. This was performed satisfactorily and the glider was deployed successfully.

Towards the end of the glider deployment there was significant pressure to recover the glider as early as possible so as not to impact with the remainder of the cruise science programme. This was surprisingly before the final MSS vertical profiler survey by the participants from Bangor University. The anticipated requirement for the glider to be deployed during MSS profiling was not evident at this time. The allocated time slot for the glider recovery was in the evening, with limited daylight remaining, after the current phase of mooring recoveries were completed. After discussions with the deck crew the conditions were deemed to be too risky to attempt a glider recovery on Thursday 27th September. Based upon the forecast of improving conditions over the next two days it was recommended that the glider recovery was postponed. This was not well received in terms of the prospective impact of this on the remainder of the scientific operations. The compromise was that the ship would be moved closer to the glider and a reassessment would be made. On further consultation with the crew and bearing in mind the failing light the feedback was that a reasonable prospect of a recovery existed. The motion of the ship and the recovery net moving relative to the glider made the recovery operations difficult. Entanglement of the glider with stay lines at the front of the net meant that the glider recovery failed on the first attempt. Subsequent efforts to hold the glider in position using long fending off poles resulted in the loss of the port wing. RRS *Discovery* was then realigned relative to the glider and a second recovery attempt was made. This time the glider was manoeuvred onto the recovery net and held in place to allow the crane operator sufficient time to lift the glider out of the water using the net. The starboard wing had lodged in the net and this was damaged during the hauling of the glider onto the starboard deck. The glider was lifted onto its transportation trolley after the recovery and washed down with fresh water. Initial status checks of the vehicle indicated no immediate hull damage and the internal vacuum had been sustained. Following this, work on servicing the glider and data recovery commenced.

The turbulence glider operations described in this report, while very successful, have indicated how precarious Slocum Electric Glider work can be from a large research vessel without the benefit of small boat support. The deployment and recovery operations used presented significant risk of glider damage or loss. This was illustrated by the impact with the glider during the deployment and the difficulty of recovering the glider. Regardless of the pressures of a busy science programme more careful attention should be paid to providing sufficient time and suitable conditions for difficult glider operations such as those described in this document. A more refined set of deployment and recovery methods are required, particularly for a less than ideal sea state. Following the work on RRS *Discovery* described in this document there were a number of recommendations suggested such as deployment slides, a lasso to be used for the recovery, lifting the glider by the moulded plastic rear tail assembly, fishing nets or trawling nets for recovering the glider, the use of navy divers to put the glider into the recovery net, a long pole operated from the deck of the ship with a snare for the glider hull section and so on. The feedback from the deck crew was that equipment of a high capital and scientific value is being put at significant risk by a "Heath Robinson contraption".

My advice still stands that underwater electric gliders are evolving and experimental oceanographic research vehicles. The only effective way to reliably deploy and particularly recover the G1 Slocum Electric Glider with a turbulence measurement capability from a large research vessel is to use a small boat such as a RHIB, with a low freeboard in a suitable sea state. The glider should be deployed and recovered using the small boat by at least two trained Slocum glider operators. In addition to this, a third person is required in the small boat to act as the boat pilot. The preferred method is to use the glider transportation trolley to deploy and recover the glider. In addition to this a tether and a surface float should also be used to assess the vehicle operation during the early phases of a deployment. This provides the required option for a safe, early recovery of the vehicle if problems arise during initial testing. If a poor sea state exists prior to a glider recovery from a remote location with a large research vessel under time constraints then a net recovery should be considered only as a final option or last resort.

During glider operations, if a glider impacts with a recovery vessel or if the glider is handled incorrectly then a breach of the glider hull seals and damage to the vehicle can occur. Any ingress of seawater into the glider poses health and safety risks along with the risk of loss of the glider. From a health and safety perspective, seawater leaking into the glider can pose the risk of a chemical reaction with the vehicle internal components, particularly the batteries. Glider operations, particularly deployment and recovery techniques and their associated sea conditions should be selected in order to mitigate these risks as far as is reasonably practicable.

What is particularly rewarding about the glider operations summarised in this document is that a novel high quality scientific data return has been achieved. A programme of developmental work has been undertaken with the turbulence glider before the D381b research cruise. The general aim of this work has been to improve the quality of the scientific measurements from the glider while providing some level of protection from damage to the fragile turbulence sensor probes. The result of this is that a track record has now been established for the successful use and operation of the turbulence glider.

Acknowledgements

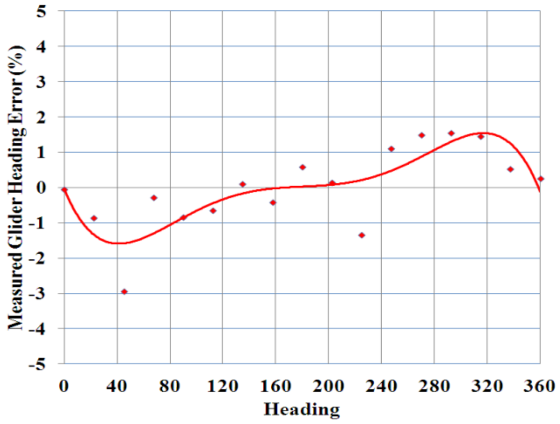
Thanks are due to Bob Seamans for the provision of a high quality work area in the University of Liverpool, Department of Engineering Hydraulics Laboratory (UOLHL). Thanks are also due to and Martin Jones for his assistance with the setting up and use of the space in the UOLHL for glider preparatory operations. This occurred at short notice and it was essential to prepare the turbulence glider for the OSMOSIS project scientific survey described in this report. Once again I owe a big thanks to the crew of RRS *Discovery* for their help and support with the challenging glider deployment and recovery operations that occurred during the D381B research cruise.

Appendix A – Glider Compass Calibration

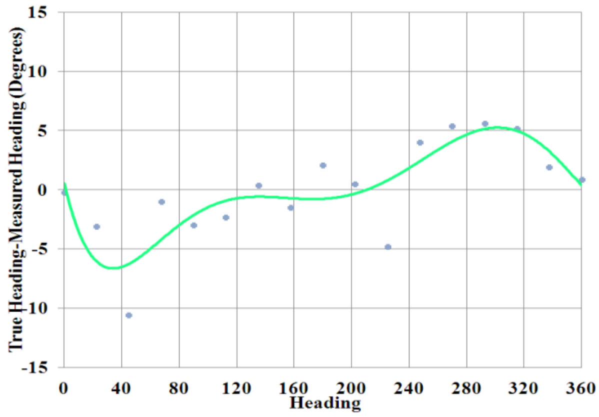
To configure the turbulence glider for the OSMOSIS deployment a set of lithium primary expendable batteries were installed. This was required to provide the capability of running the required glider science sensors at their maximum recording rates for extended periods of time of weeks in duration. Any disturbance in the glider configuration such as the installation of new batteries or sensor drift over time can compromise the operation of the glider internal electronic compass. To ensure the integrity of the compass measurements in the glider a compass calibration was undertaken before the OSMOSIS glider deployment. This involved taking the glider to an open space free of stray electrical or magnetic fields, calibrating the compass and then verifying the result of the calibration. During this process the glider is reoriented through a series of positions involving changes to pitch, heading and roll while the internal compass samples the external magnetic fields. Provided that a satisfactory spread of glider movements is achieved with the required time frame of typically 5 minutes the glider compass can then self calibrate. If successful the electronic compass module nulls the effect of any static fields that are introduced by such factors as changes in the internal glider components. The result of this is to improve the accuracy of the compass. To check the integrity of a compass calibration the measurements of the glider electronic compass are compared to measurements from a hand held magnetic compass. The glider is basically rotated horizontally through 360° in a series of iterations. At each of these iterations of normally 22.5° the glider heading measurement is compared to readings from a magnetic compass. Although this is a practical procedure and subject to experimental error the process provides a basic check that a glider compass calibration has been performed satisfactorily. A selection of images of the turbulence glider compass calibration process is shown in Figs A1 and A2.

Fig. A1. Turbulence Glider Electronic Compass Check for the OSMOSIS Deployment

After reorienting the glider during the compass calibration procedure a board with a reference line is aligned in fixed steps through 360° using a handheld magnetic compass. The glider is then aligned with this reference line on the board and the glider heading is compared to the magnetic compass reading. The glider electronic compass was recalibrated at Birkenhead Park, Wirral, UK on 21st August 2012.



b Glider to magnetic compass comparison as a percentage of 360°



c Glider actual heading and measured heading difference

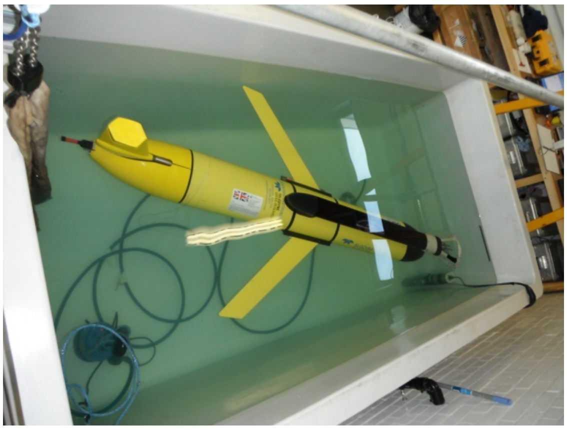
Fig. A2. Turbulence Glider Electronic Compass Calibration Measurement Check

The results from the glider compass calibration and subsequent heading check procedure confirmed that the calibration process had been successful. A peak heading error of approximately 5° was recorded with a value significantly less than this for most of the calibration check procedure. This verified that the turbulence glider internal navigational electronic compass had been successfully recalibrated following the installation of the lithium primary battery packs for the OSMOSIS project deployment.

Appendix B – Ballasting Configuration and Testing

Before a deployment of a glider and particularly after an exchange of internal components of the glider such as batteries the glider must be accurately ballasted for the intended survey area. This ensures that the buoyancy pump in the glider has sufficient range to efficiently operate the vehicle during the required dive and climb cycles. For extended endurance with the micro-Rider turbulence probe, lithium primary expendable batteries were installed. This resulted in a reduction in an overall mass of the battery packs of approximately 5kg when compared to the standard alkaline battery packs that were previously installed. A custom weight assembly was installed in the science bay in the centre of the glider to compensate for the bulk of this mass change. A saltwater ballasting tank and work area was then setup in the University of Liverpool Hydraulics Laboratory (UOLHL). Figure B1 shows a sequence of pictures of the glider ballasting and preparation area. After the ballasting tank was filled to approximately 75% capacity with fresh water, synthetic sea salt was mixed into the ballasting tank to simulate the intended glider deployment conditions. Internal weights that were mounted at strategic points inside the glider were carefully and iteratively trimmed. This involved assessing the vehicle ballasting in the tank, removing the glider from the tank, washing the glider down and drying the glider outer hull. The glider was then disassembled and then any adjustments to the internal trim weights that were required were implemented. The glider was then reassembled and this process was repeated until satisfactory ballasting of the glider was achieved.

a The University of Liverpool Hydraulics Laboratory glider preparation area



c Glider ballasting trials in a saltwater test tank

Fig. B1. Turbulence Glider Ballasting

The basic conditions for the UOLHL ballasting tank were determined from previous records for the PAP site in the Celtic Sea for September. These consisted of mean values for water quality readings in the first 150m of the water column as shown in Table B1.

Table B1 PAP Site Mean Upper Water Column Values for Glider Ballasting

Temperature (^oC)	Salinity (PSU)	Density (Kg/m^3)
14	35.3	1026.4

The UOLHL facility was then used to ballast the glider. The use of a ballasting tank at room temperature resulted in the following parameters being used in the UOLHL tank to simulate the anticipated deployment conditions, as listed in Table B2.

Table B2 UOHL Glider Ballasting Conditions

Temperature (^oC)	Salinity (PSU)	Density (Kg/m^3)
21.7088	38.179	1026.73

The elevated temperature and salinity value that were required for the UOLHL tests prompted understandable concern about the procedure used. A further ballasting test was deemed necessary during the RRS *Discovery* based D381B research cruise. At the PAP site the following values were obtained from the ship's CTD at a GPS location of 48° 35.150'N, 16° 3.458'W at 13:00 GMT on Monday 17th September 2012. Using the Teledyne Webb Research (TWR) ballasting spreadsheet the estimations of the glider mass changes between the ballasted settings and the actual values in the water column was derived, as listed in table B3.

Table B3 Turbulence Glider Ballasting Changes Required for Neutral Buoyancy

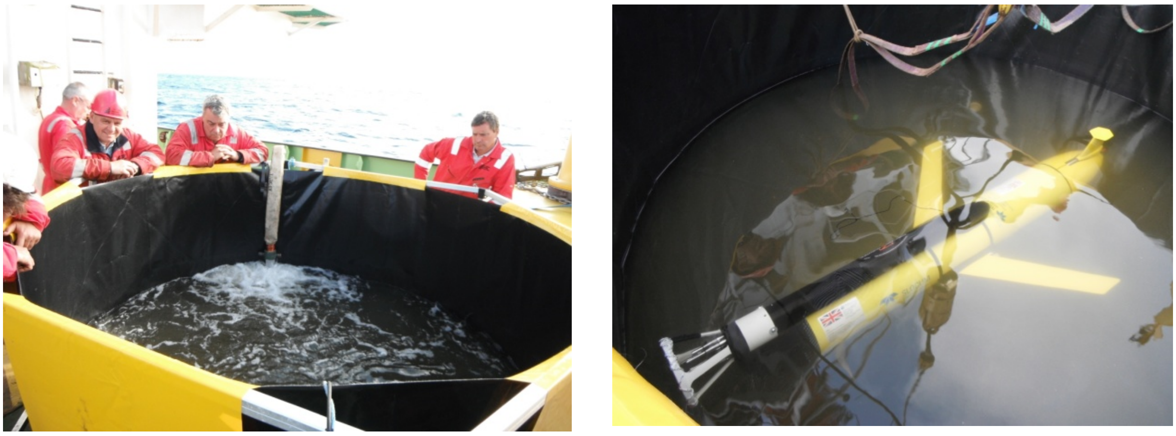
Water Depth (m)	Temperature (°C)	Salinity (PSU)	Density (Kg/m^3)	Ballasting weight change required (g)
12	17.65	35.53	1025.81	-71
50	15.5	35.58	1026.53	-49
100	12.98	35.67	1027.36	-24
150	12.4	35.6	1027.65	-23

Considering that the glider should be ballasted slightly heavy based upon the ship's CTD measurements a tank test was then undertaken to confirm the glider ballasting. Just prior to the lowering of the glider into the test tank a CTD was performed of the tank water using the recently recalibrated Seabird Microcat, serial number 5434. The results of the ballasting tank test are listed in table B4.

Table B4 UOHL Glider Ballasting Conditions

Temperature (°C)	Salinity (PSU)	Density (Kg/m^3)	Ballasting weight change required (g)
18.2460	35.5833	1025.65	-75

After the glider was placed in the tank and purged of any trapped air pockets, bubbles and so on the glider was well ballasted and floated just below the water surface in the tank. The glider, micro-Rider turbulence probe and guard assembly were also level, with minimal parasitic pitch and roll. This indicated a good setup of the glider had occurred and that the UOLHL ballasting has produced settings that are lighter than expected by several tens of grams. Figure B2 shows photographs of the turbulence glider ballasting tests onboard RRS *Discovery* using a portable tank. Considering that the glider buoyancy pump has a capability for mass changes of approximately ± 250 grams the decision was then made to deploy the glider.



a Filling of the portable tank with near surface seawater from the Celtic Sea PAP survey site

b The turbulence glider was confirmed as being correctly ballasted during the tank test

Fig. B2. Turbulence Glider Ballasting Tests Onboard RRS *Discovery*

Appendix C – Preliminary Turbulence Glider Recorded Scientific Data Assessment

This section provides a brief overview of an initial quality check undertaken on the turbulence glider and micro-Rider recovered data. This scientific data was generated during the OSMOSIS project deployment from RRS *Discovery* between Monday 17th September and Thursday 27th September 2012. The glider was operating within the Celtic Sea PAP mooring site location.

C1 Glider CTD Data Assessment

A time series of the glider CTD recorded temperature and salinity data is shown in Figures C1 and C2.

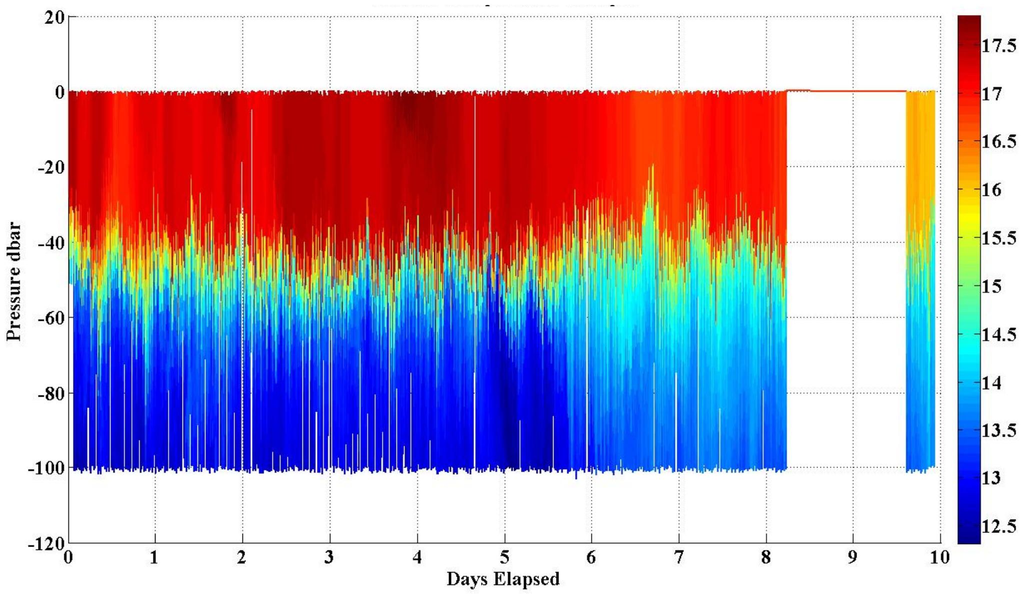


Fig C1 Plot of Temperature Versus Depth for the 10 Day deployment

The CTD has stopped logging data for ~1.5 days from ~8.25 to 9.75 days into the 10 day deployment, leading to an interruption in the temperature record.

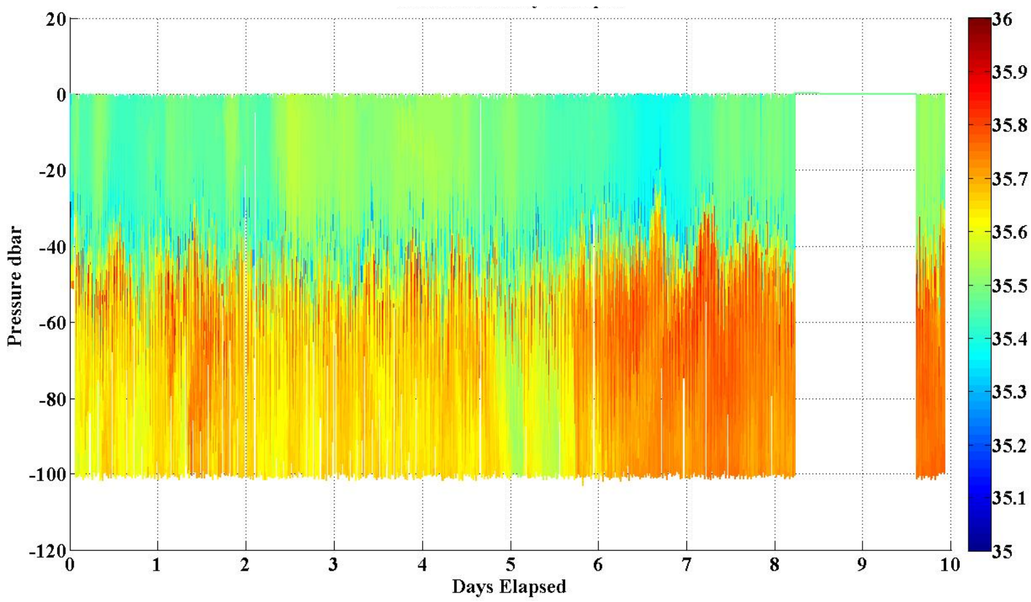


Fig. C2 Plot of Salinity Versus Depth for the 10 Day deployment

The CTD has stopped logging data for ~1.5 days from ~8.25 to 9.75 days into the 10 day deployment as illustrated by the loss of derived salinity values between day 8 and day 9 in this plot.

C2 Initial Turbulence Glider Micro-Rider Data Assessment

A diagram of the micro-Rider turbulence probe configuration is shown in Fig. C3 with the shear probe sensitivities and orientation specified. Following this a series of plots are included to provide a basic initial assessment of the micro-Rider recorded data quality.

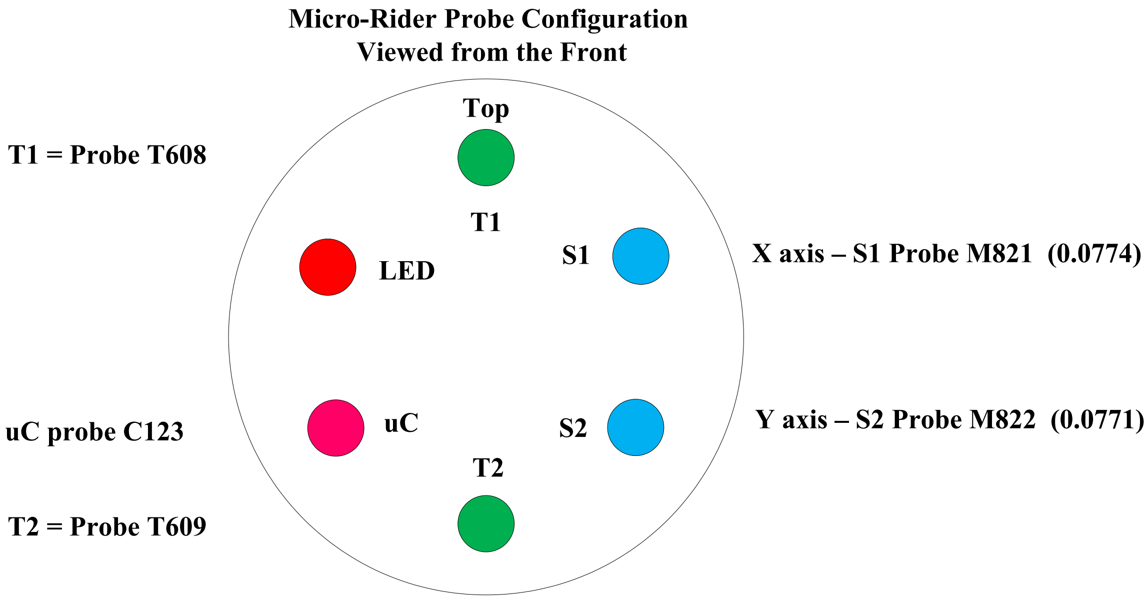
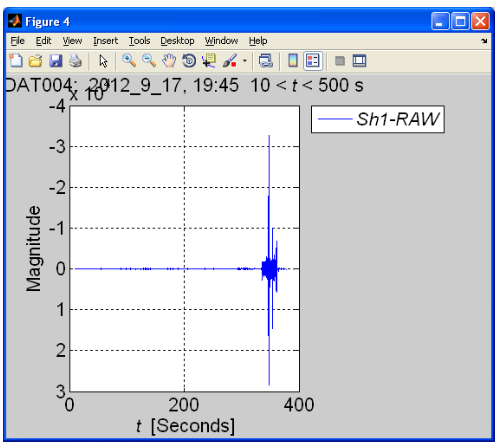
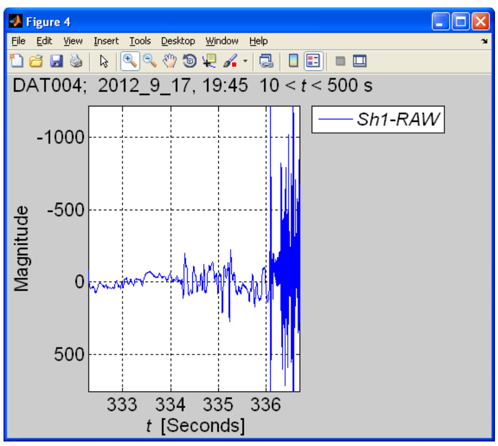


Fig. C3. Turbulence Glider Probe Configuration Diagram

Note that the shear probe axes specified represent the orientation of the transducer. Each probe will measure shear forces acting in a direction that is normal to the shear probe orientation.

Data quality checks for file Dat004.p that was recorded on 17th September 2012. This was generated by the micro-Rider near the start of the data set during 50 metre test dives. Up-cast or climb phase measurements have been generated and all channels appear to be working correctly. Figures C3 to C8 show a selection of plots of the recorded data.

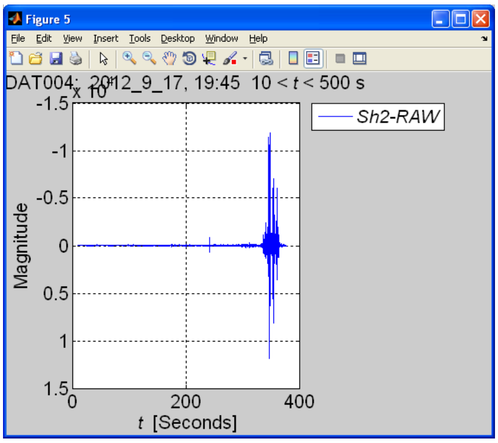




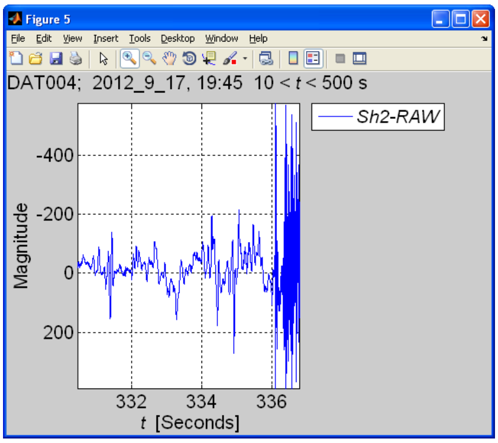
a Raw signal

b. Expanded view. The dynamic measurement range up to an inflection (glider motor noise) is shown

Fig. C4 - Dat004.p – Shear Channel 1 Signal Magnitude versus Time Elapsed

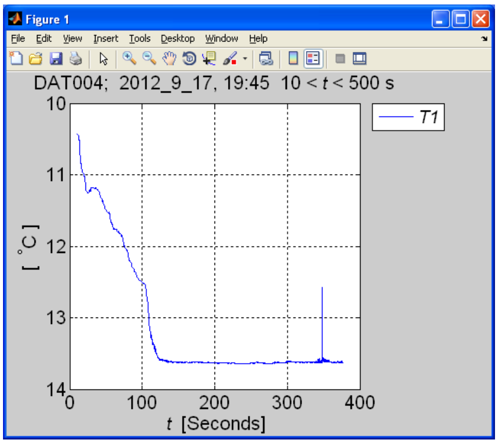


a Raw signal

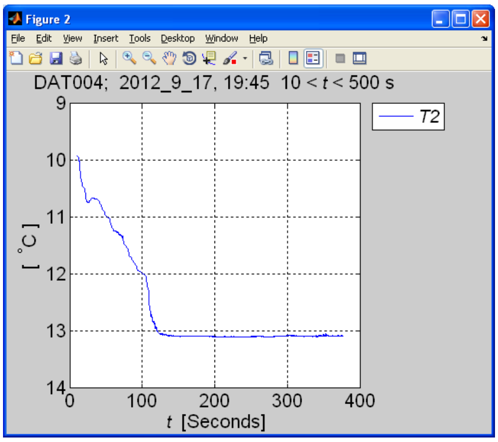


b. Expanded view. The dynamic measurement range up to an inflection (glider motor noise) is shown

Fig. C5 - Dat004.p – Shear Channel 2 Signal Magnitude versus Time Elapsed

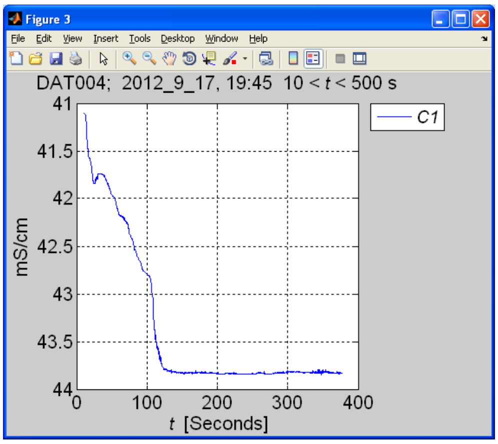


a Temperature Channel 1

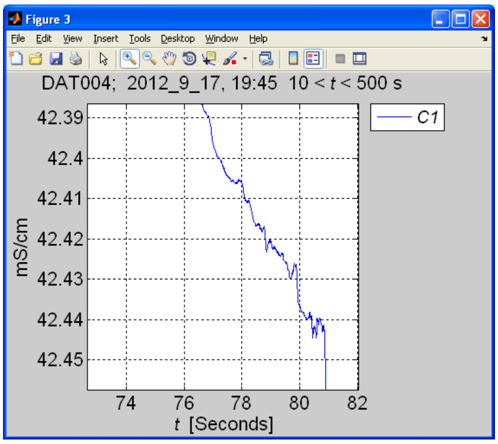


b Temperature channel 2

Fig C6 - Dat004.p – Temperature Channels



a Full profile



b. Expanded view. The micro-conductivity probe response seems to be correct without any evidence of fouling.

Fig. C7 - Dat004.p – micro-Conductivity

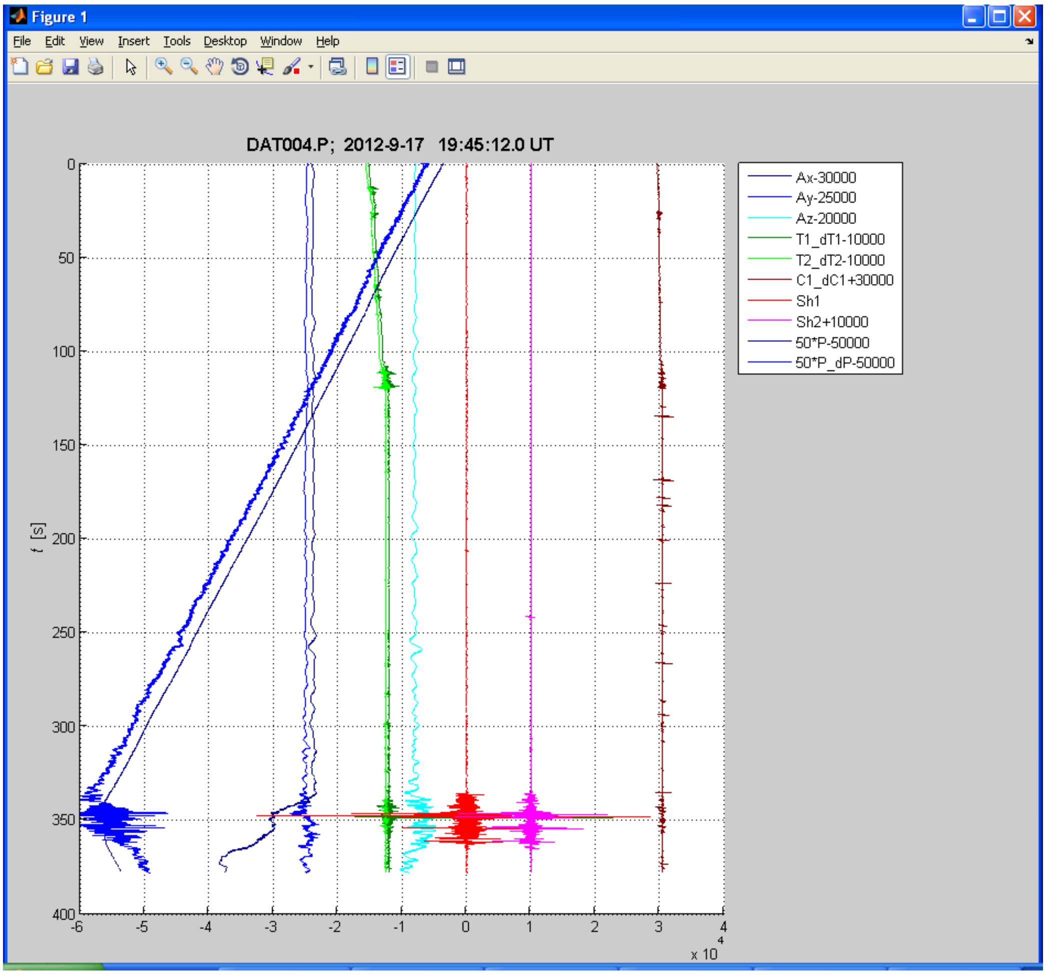
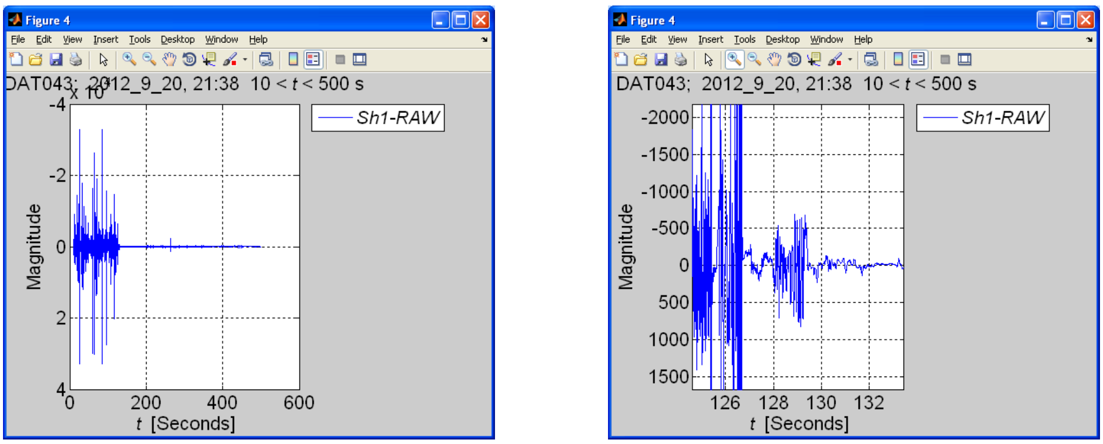


Fig. C8 - Dat004.p – Plot VMP Function

This is a plot with the raw measurements from the micro-Rider turbulence probe normalised onto a common x axis. The pressure measurements, all of the turbulence channels and the accelerometer measurements seem to be operating correctly.

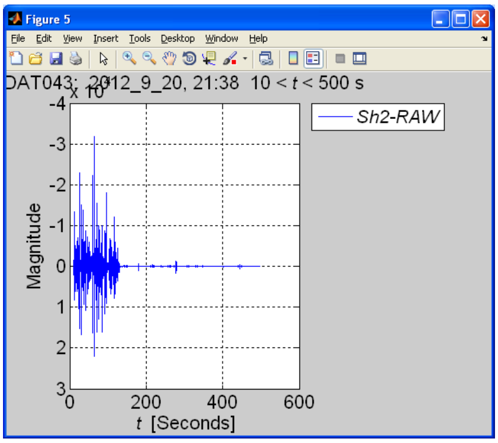
Data quality checks for file Dat043.p that was recorded on 20th September 2012. This was generated by the micro-Rider 3 days into data recording during full 100m dives and climbs. The required measurements have been generated and all channels appear to be working correctly. Figures C9 to C13 show a selection of plots of the recorded data for the dive phase of an underwater glider profile.



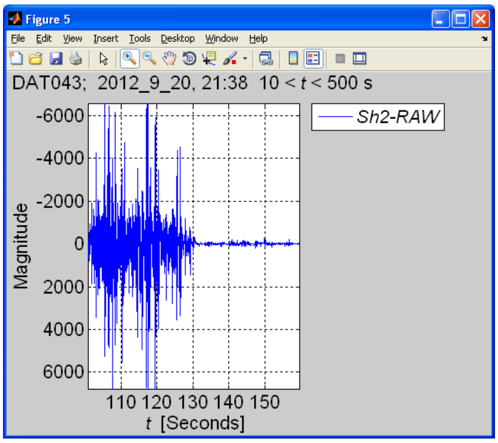
a Raw signal

b. Expanded view. The dynamic measurement range after an inflection (glider motor noise) is shown.

Fig. C9 - Dat043.p – Shear Channel 1 Signal Magnitude versus Time Elapsed

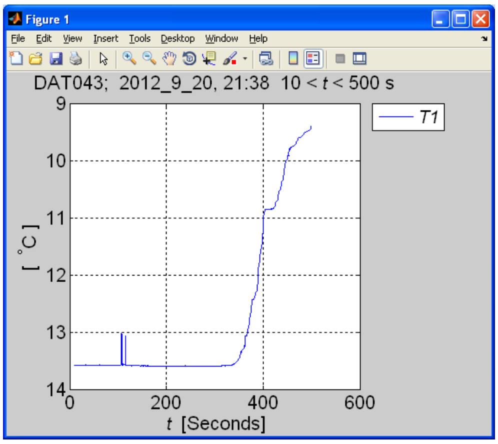


a Raw signal

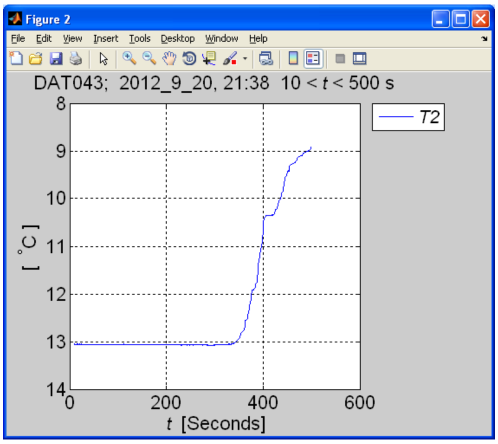


b Expanded view. The dynamic measurement range after an inflection (glider motor noise) is shown.

Fig. C10 - Dat043.p – Shear Channel 2 Signal Magnitude versus Time Elapsed

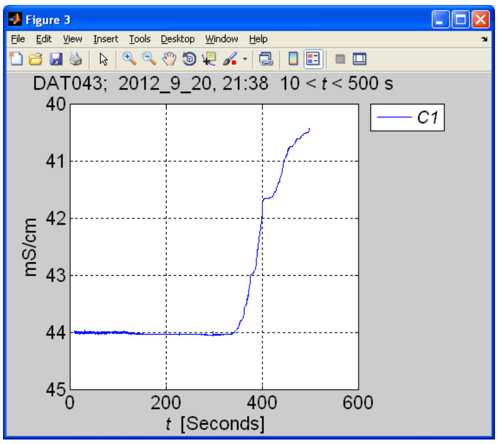


a Temperature Channel 1

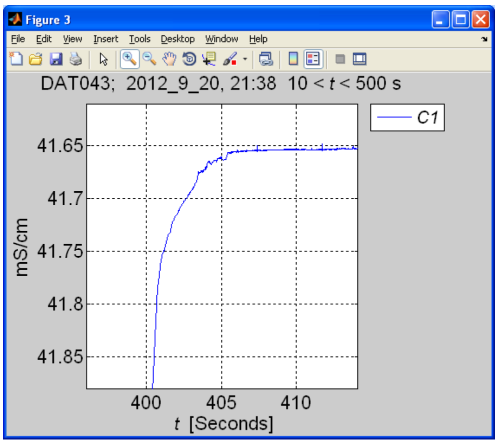


b Temperature channel 2

Fig. C11 Dat043.p – Temperature Channels



a Full profile



b. Expanded view. The micro-conductivity probe response seems correct without any evidence of fouling.

Fig. C12 - Dat043.p – micro-Conductivity

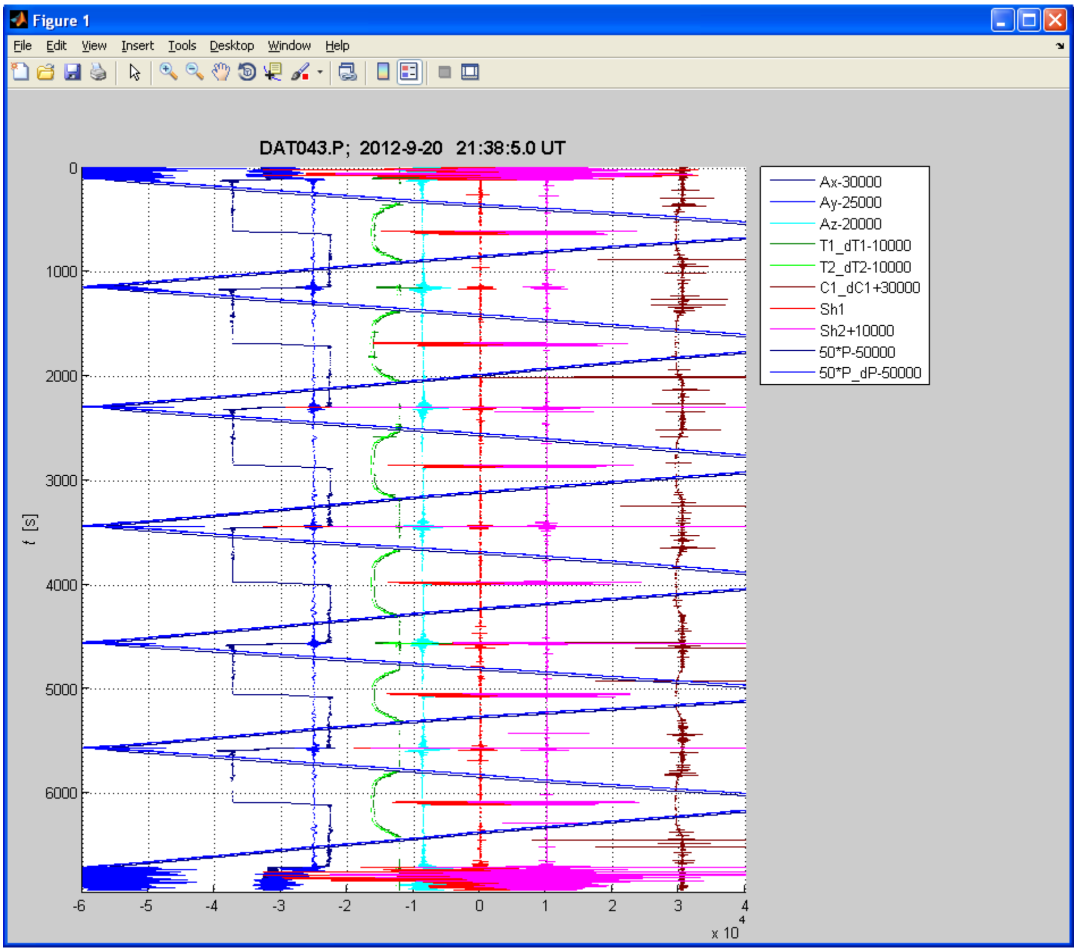
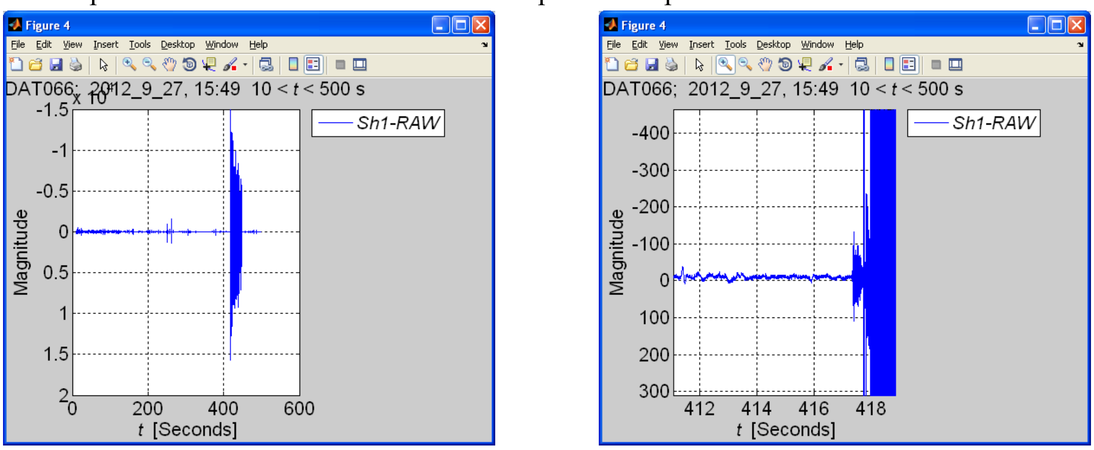


Fig. C13 - Dat043.p – Plot VMP Function

This is a plot with the raw measurements from the micro-Rider turbulence probe normalised onto a common x axis. The pressure measurements, all of the turbulence channels and the accelerometer measurements appear to be operating correctly. This data file contains multiple profiles.

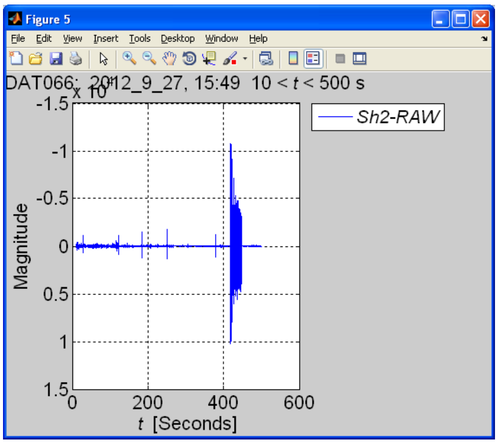
Data quality checks for file Dat066.p that was recorded on 27th September 2012. This was generated by the micro-Rider during a glider dive at the end of the deployment. The required measurements have been generated and all channels appear to be working correctly. Figures C14 to C18 show a selection of plots of the recorded data for the dive phase of a profile.



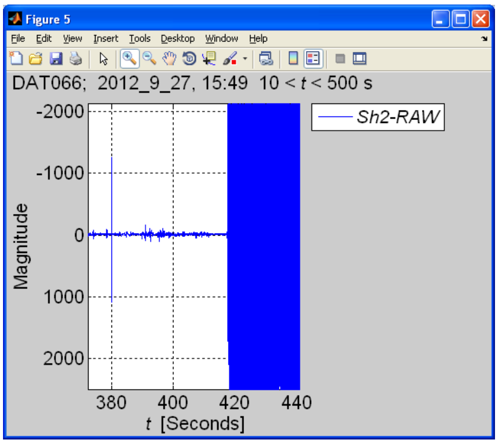
a Raw signal

b. Expanded view. This shows the dynamic measurement range up to an inflection (glider motor noise)

C14 - Dat066.p – Shear Channel 1 Signal Magnitude versus Time Elapsed

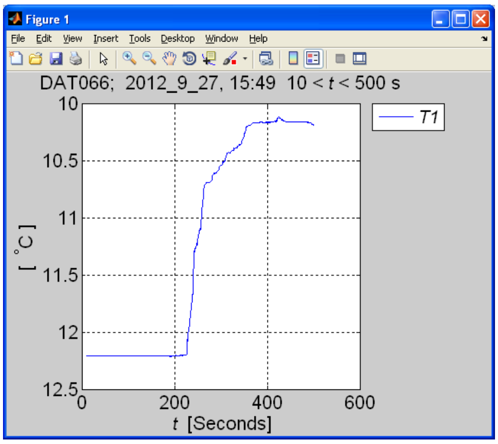


a Raw signal

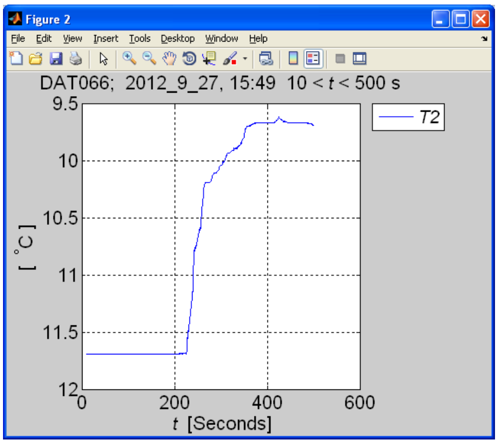


b Expanded view. This shows the dynamic measurement range up to an inflection (glider motor noise).

C15 - Dat066.p – Shear Channel 2 Signal Magnitude versus Time Elapsed

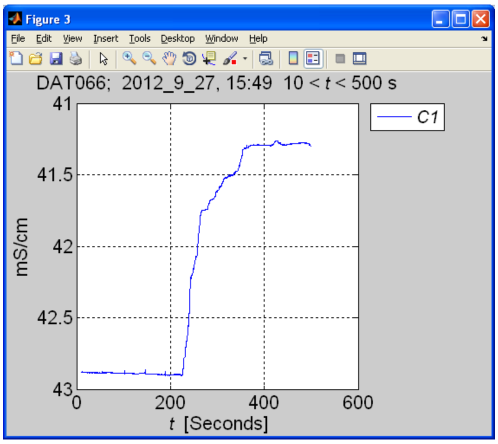


a Temperature Channel 1

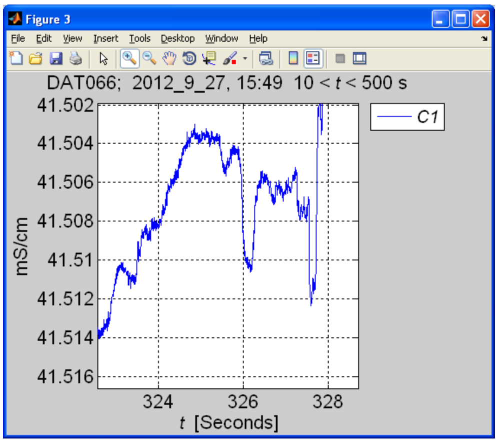


b Temperature channel 2

C16 - Dat066.p – Temperature Channels

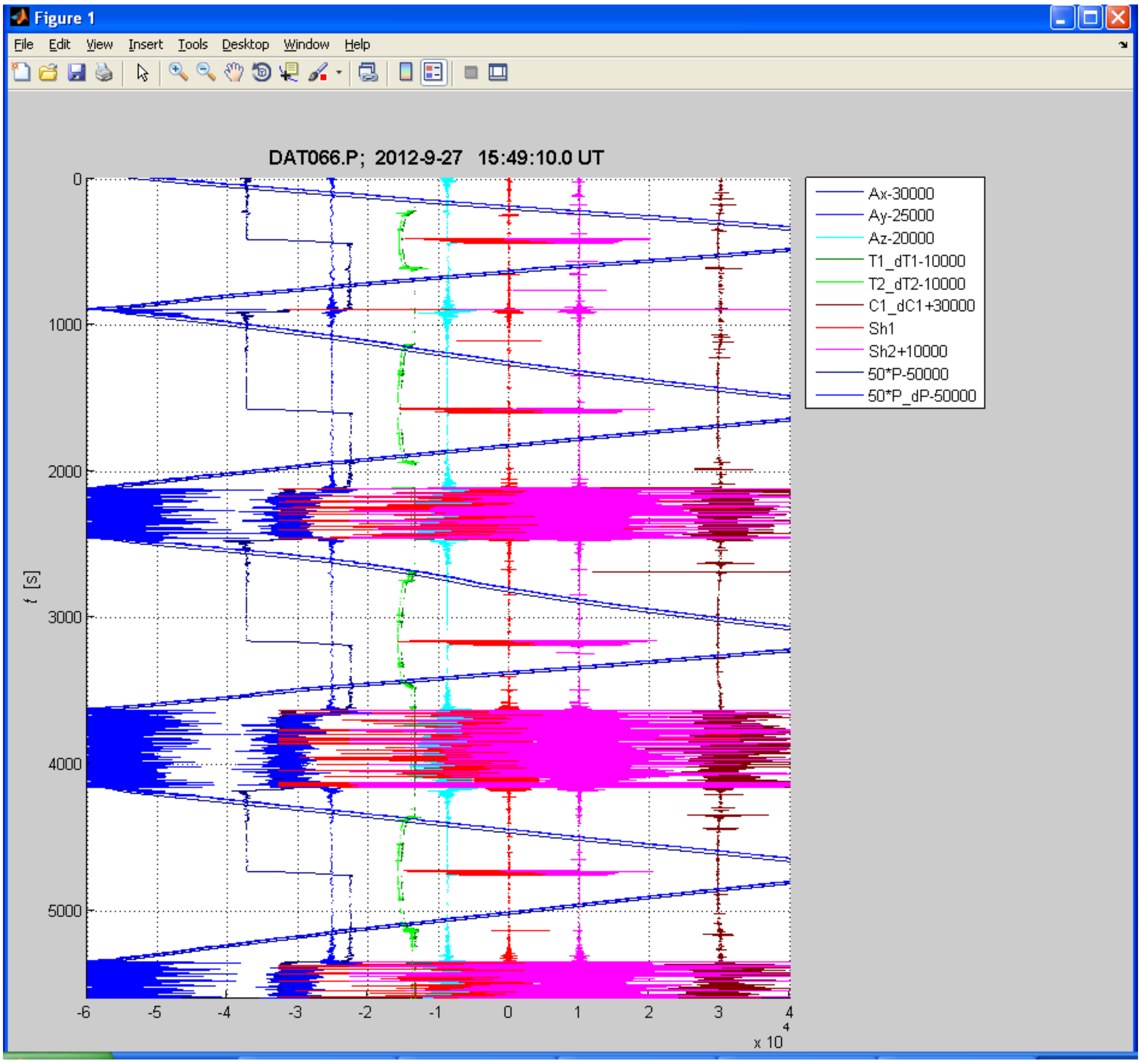


a Full profile



b Expanded view. The micro-conductivity probe response seems to be correct without any evidence of fouling

C17 - Dat066.p – micro-Conductivity



C18 - Dat066.p – Plot VMP Function

This is a plot with the raw measurements from the micro-Rider turbulence probe normalised onto a common x axis. The pressure measurements, all of the turbulence channels and the accelerometer measurements appear to be operating correctly. Multiple profiles have been recorded in this data file. The noise envelope in the plots shows an inflection. The single dive and climbs during the 30 minute profiling underwater prior to the glider recovery are evident towards the lower portion of the plot.