Autosub6000: Results of its Engineering Trials and first Science Missions

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Abstract

In September 2007 on *RRS Discovery*, the Autosub6000 Autonomous Underwater Vehicle (AUV) completed its first deep water engineering trials, and less than a year later, fitted with a multibeam bathymetric mapping sonar, carried out its first science missions, as part of a geology and geophysics science cruise onboard the *RRS James Cook* to investigate potential geo-hazards (such as tsunami generating landslides) on the European and North African margin. In the spirit of true AUV autonomy, while the AUV was deployed, we used the ship for seabed coring operations, and once the AUV was recovered, the high resolution bathymetry which it had obtained guided the next coring operations. In this paper we will describe how we are tackling the issues that specifically affect a deep diving AUV capable of operating with true autonomy, and independently of the mother ship: How to carry enough energy for long endurance and range? How to operate safely and efficiently with varying buoyancy? How to maintain accurate navigation throughout missions lasting up to several days?

Introduction

Worldwide there are several scientific survey AUVs which are either operational or in advanced stages of development. For example, the WHOI's Autonomous Benthic Explorer (ABE) has been carrying out pioneering work in high resolution mapping of mid ocean ridge environments for over ten years [1]. This will be soon to be replaced by the SENTRY AUV. Hydroid, with the 6000m rated REMUS 6000, MBARI, with the Seafloor Mapping AUV [2], Altium technologies, with BLUEFIN-21, and International Submarine Engineering, with its Explorer class AUVs [3], all manufacture AUVs with deep sea science capabilities However, the field is still relatively immature and (with the exception of ABE), and there is relatively little published literature on the science results of AUV missions beyond 3000m deep.

Ever since its since its conception and first trials in 1996, we have emphasised the “Auto” in the Autosub programme name. We have always placed great importance upon freeing up the support ship to carry out other operations, and have routinely operated the vehicle “over the horizon”, beyond communication or acoustic tracking range. For example, during the Arctic and Antarctic under ice missions (as part of the UK, Natural Environmental Research Council funded Autosub Under Ice programme),we operated the AUV for a 24 hour missions under sea ice, North East Greenland [4], and a 30 km run under an Antarctic ice shelf [5]. In both of these missions the AUV operated well beyond any communications range, or hope of rescue if anything went wrong. For these under ice and other science missions, we developed the control, collision avoidance and navigation systems for the AUV, and gained experience of operating an AUV in extreme environments [6].

We have continued with this philosophy of true Autonomy for the Autosub6000 AUV. For example, while the AUV is carrying out a high resolution bathymetric survey, we may wish to use the mother ship for coring, perhaps guided by data previous recorded by the AUV.

There are several challenges to achieving the required performance. For useful autonomy we need to consider and develop the energy storage technology. Another potential problem is the buoyancy variation of the AUV as it descends. This could cause an increase in the hydrodynamic drag, and hence decrease the useful range of the AUV.

Unassisted navigation of a deep diving AUV is another challenge. An AUV fitted with currently available multibeam sonars is capable of bathymetric surveying at a resolution 1 to 5 m (depending on the AUV flying altitude). The value of this data is maximised if we can position the vehicle with corresponding accuracy, particularly if the AUV is being used to identify interesting seabed features for later, more detailed, investigation by itself or another vehicle (for example a Remotely Operated Vehicle).

Hence there are three issues for an AUV platform which are *specific* to the *deep* diving and *true autonomy*:

- Energy storage at high ambient pressures.
- Accurate autonomous positioning of the vehicle throughout its mission.
- Buoyancy change due to compressibility effects.

Autosub6000 Mechanical Design

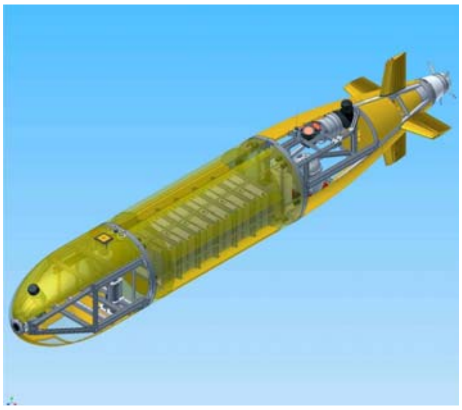

Figure 1 - Layout of Autosub6000. The forward and aft sections are free flooded, with glass fibre reinforced plastic (GFRP) fairings.

Autosub6000 is 5.5 m long, with a 2.8 m^3 displacement and a 6000 m depth rating The main difference between it, and its predecessor, the 1600 m depth rated Autosub3 (described elsewhere [7]), is in the centre section (Figure 1). Whereas the Autosub3 uses 7, 3 m long carbon fibre pressure cases, containing up to 600 kg of primary manganese alkaline cells, Autosub6000 uses a completely different approach. The centre section contains no pressure cases, it is essentially a cylinder made from sections of syntactic foam (Emerson and Cuming, EL34 – density 580 kg m^{-3}), with slots cut out for up to 12 batteries. The navigation and control systems are contained within titanium pressure cases in the free flooding tail section. The 1.5 long free flooding nose section is free for the science payload

Batteries

We achieved the usually mutually exclusive characteristics of deep diving capability and good range by developing a pressure balanced lithium polymer battery technology, thereby eliminating the need for expensive and bulky pressure housings. This approach was first pioneered for use in AUVs by Bluefin robotics [8]. Using our deep pressure facilities at NOC (up to 68 Mega Pascal), we have carried out extensive pressure cycle testing of the batteries (Figure 2).

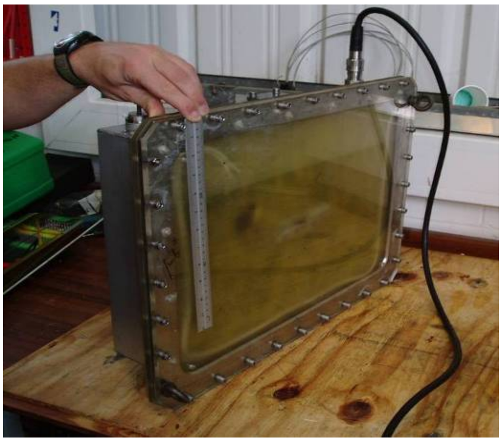

Figure 2 - A pressure balanced battery.

Within each battery box are 405 Kokam Lithium Polymer cells, storing a total of 16.2 M joule (4.5 kW hr) of energy at a nominal 57 volts, at up to 15 Amperes discharge rate. The batteries are protected against over charge, over discharge, and over current, though fail safe, redundant circuitry. Each battery is monitored for currents, voltages, temperature, pressure compensating oil level, and leaks. They weigh 44 kg in air (22 kg in seawater), while the dimensions are 569 x 421 x 135 mm. With charge monitoring and control integrated into the battery, charging is relatively simple, only requiring a standard 1.2 kW power supply with current limit operation for each battery.

Autosub6000 is currently fitted with 4 pressure balanced batteries, giving, with a multibeam sensor payload (120 W power), an autonomy of 36 hours and a range of 180 km. There is capacity in the vehicle to increase this to 12 batteries with a proportional increase in range and endurance (longer ranges are possible at slower operating speeds).

Autosub is propelled by a direct drive brushless d.c. motor, and two bladed propeller.

Navigation, communications and Tracking

For dead-reckoned navigation, the AUV uses a 300 kHz Teledyne RDI Workhorse Acoustic Doppler Current Profiler (ADCP) to measure its velocity relative to the seabed (when within the 220 m seabed tracking range), and an Oceano Ixsea PHINS, Fibre Optic Gyro (FOG) based Inertial Navigation System (INS). These are housed together in a titanium pressure case (Figure 3). Our own and other operator's [9] experience with similar navigation systems, indicate that when calibrated, the drift rate of this system is 5 m per hour or less.

There remain two problems for the accurate navigation for a deep diving AUV:

- The initial position problem: Positioning of the AUV after its initial descent to the seafloor.
- The drift problem: Controlling and correcting the navigation drift error for long missions hours.

Both of these problems could be tackled by the use of a seabed moored acoustic transponder network. However, this approach is expensive in ship time. It has been reported [10] that to deploy, position, and recover 5 transponders at 4800 m water depth, for acoustic navigation of the ISIS ROV within a square box of only 1 km side, took a total of 27 hours of ship time. The AUV could survey 40 km^2 in this time. Use of an Ultra Short Base Line (USBL) system from the mother ship is also unattractive, as it commits the ship to continuously tracking the AUV.

Figure 3 - The Autosub6000 Navigation System.

Instead we are using a technique of range only navigation: A set of ranges from the ship to an acoustic transponder on the AUV, when combined with the AUVs own dead reckoned navigation and the ships navigation, provide the information to accurately position the vehicle after its descent. This approach avoids the main problem with USBL based systems – their need for extremely high pointing and attitude reference accuracy, necessitating a costly and very precisely calibrated system [11].

There remains the challenge of controlling the drift of the AUV positioning system during the mission. For missions where an area is to be surveyed by the AUV, there is much interest in approaches such as Simultaneous Localization and Mapping (SLAM) [12]. We are planning to use a similar approach with Autosub6000. Using data from the Kongsberg Simrad EM2000 multibeam bathymetric mapping system, fitted to Autosub6000, we are developing algorithms based on correlation, or Terrain Contour Mapping (TERCOM) approaches, to substantially eliminate the uncontrolled navigation error growth during area survey type missions.

We use a combined USBL and bi-directional acoustic messaging system, the Linkquest Tracklink 10000, for real time tracking of the AUV from the mother ship, and telemetry for health monitoring and command.

Buoyancy Change

If the materials used in the construction of an AUV do not compress at a similar rate to that of seawater itself (2.8% over 6000 m) the buoyancy of the vehicle will change substantially as it descends. The largest solid item on the vehicle is the syntactic foam used for buoyancy. Prior to the initial trials, from manufacturers data, and laboratory tests, we were able to get an approximate estimate of the bulk compressive and thermal moduli of this material, and also account for the other materials used in the construction of the vehicle (which generally compress little). However, prior to the first trials there remained significant uncertainty, and we could not guarantee that the vehicle would stay buoyant at all times. So, for the first trials, we conservatively ballasted the vehicle with a surface buoyancy of 20 kg (rather than the typically used 10 kg for Autosub3 - a larger vehicle), and also installed two independent emergency weight drop systems, each able to increase the vehicle buoyancy by 10 kg, in an emergency situation (e.g. when over depth is detected).

This conservative level of surface buoyancy (together with the expected increase in buoyancy with depth) could create a problem. The vehicle might have difficulty controlling its depth or suffer significantly increased drag due to the need to produce large hydrodynamic downward force. The solution was to install small wings on the body set slightly pitch down. These help by more efficiently producing down force than can the vehicle body alone.

Results - Autosub6000 sea trials in September 2007

Autosub6000's first test cruise, and first time in water, was in September 2007, onboard the *RRS Discovery*. We headed for a flat part of the deep abyssal Atlantic with a water depth of 4680m. near 47^0 N, 11^0 W, 250 miles from Falmouth, UK, the embarkation port.

We needed to plan the first deep mission with some care for its first dive to 4556 m. We could not assume that any system (including the acoustic communications system, which had never been tested on the vehicle) would work as designed. Shortly after daybreak on September 22^{nd} 2008, we launched Autosub6000. Following system checks via the radio link, we sent the command to start the mission. The vehicle dived and spiralled down to 1000 m depth, and then began circling beneath the ship. We were relieved that the acoustic telemetry system worked faultlessly, as we received engineering data of the vehicle state as it descended. We were particularly interested to monitor the pitch, forward speed, and stern plane angles. When flying at constant depth these variables are related to the vehicle buoyancy (Equation 1) and hence can be used to monitor the change of buoyancy as the vehicle descends.

$$B = \frac{1}{2}\rho U^2\left(CL_{body}\emptyset + CL_{Splane}\delta\right) \qquad (1)$$

Where B = AUV Buoyancy, ρ=density of water, U =AUV speed through the water, CL_{body}= lift slope of AUV body, CL_{splane}=lift slope of sternplane, ϕ=pitch angle, δ=sternplane angle.

Having collected enough data to be satisfied that the vehicle was operating correctly, we sent an acoustic command for the vehicle to continue its descent to 2500 m. If the AUV had not received this "continue" command within a period of 1 hour since reaching 1000m, it would have automatically aborted its mission, dropping its 20 kg ballast weights and surfaced. This mode of behaviour is inherently failsafe. If the vehicle had gone out of control, and/or we couldn't establish acoustic communications, the vehicle would abort the mission and start to ascend before it could collide with the seabed.

Communications and Navigation

One of the objectives of the trials was to test the performance of the Tracklink 10000, telemetry and USBL system, and test our procedures and algorithms for navigating the AUV using range-only measurements. Figure 4 is a plot of the AUV navigation (uncorrected) for the first deep mission.

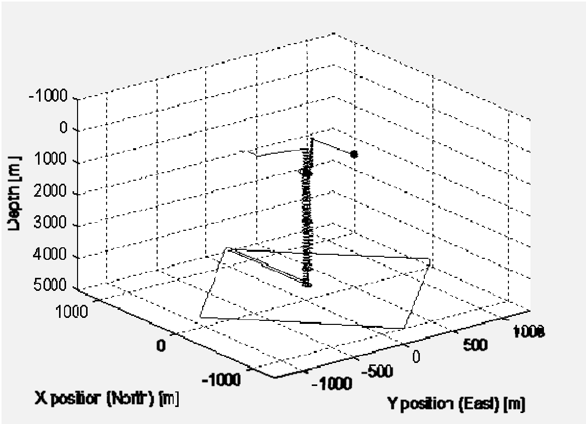

Figure 4 - 3D Navigation plot for the first deep Autosub6000 mission. The AUV spiralled to depth then executed a 1km side box at 4556 m depth.

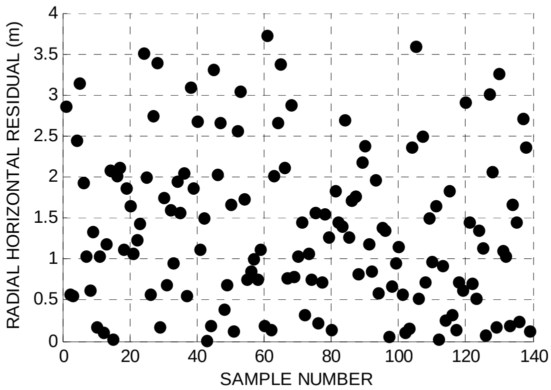

Figure 5 - The absolute values of horizontal range residuals for all of the ranges measured between the ship and the AUV as the AUV executed a 1 km side box around the ship at 4556 m depth.

By combining the AUV's own self navigation (as it executed the 1 km side, square course around the ship, at 4556 m depth and an altitude of 120 m above the seafloor), with the ships navigation, and the ranges from the ship to transponder on the AUV, we were able to calculate the amount by which the AUV navigation had drifted during its descent to the seabed. The solution in this case was, East: -368m, North: 848m. One approach to estimating the robustness and accuracy of this approach is to evaluate the solver residuals (calculated for the horizontal radial error), for each of the 130 range measurements (Figure 5). The low scatter and maximum values of these residuals is a strong indicator of the robustness of this method. The solver uses all of these data to produce a single position estimate. Very similar results are be obtained by using only 10 ranges.

After its seven hour first dive the vehicle surfaced, and was recovered onto the launch and recovery system (Figure 6).

On subsequent dives we programmed the AUV to head south for 5 km and back, while the ship remained more of less stationary. The USBL and telemetry system tracked, and continued to reliably send and receive telemetry messages up to a horizontal range of 7000 m, confirming the suitability of the system for AUV operations to its depth limit of 6000 m.

Results - RRS James Cook Cruise 027

Following the successful engineering trails, it was arranged for Autosub6000 to be a part of *RRS James Cook* Cruise 27. Lead by Dr Russell Wynn of the National Oceanography Centre, Southampton, the objective of the cruise was to investigate potential threats to coastal communities along the western European margin from tsunamis generated by giant landslides and earthquakes.

For this cruise, Autosub6000 was fitted with a Kongsberg Simrad EM2000 multibeam bathymetric sonar. Mounted on the underside of the nose section of Autosub (with the hydrodynamic fairing), (Figure 6), the system isonifies the sea bed with a 120 degree swath of 111 beams. Flying at 100 altitude, the total swath width is 346 m. For the first mission, we conservatively set the line spacing of the swaths at 200 m. Results from the first mission showed, however, that the full swath width was measured 100% of the time, and the navigation displayed negligible drift between lines. For subsequent missions we set the line spacing at 300 m. With a vehicle speed of 5 km per hour, this produced an area coverage rate of 1.5 km^2 per hour. The bathymetric data was displayed at a resolution of 2 m.

The intention was that Autosub6000 would carry out a high resolution multibeam survey of an area, and once recovered, the data would be used to guide locations for seabed sampling using piston cores (Figure 7). For this to be successful, it was important that the positioning of the Autosub was accurate, both in real time (so that the correct area is surveyed), and after post mission processing (so that the navigation corrected data could be used to guide coring operations).

The missions

Each of the missions were based on the same template, allowing us to develop standard mission planning tools, which very much simplified (and hence made more reliable) the mission planning process. The only parameters which needing setting for each mission were :

- Position centre of the survey area
- Width and length of the survey box
- Line spacing (200 m initially, increased to 300 m after the first mission)
- Survey altitude (always 100 m)
- Minimum water depth in the survey area (by taking this into account, we could increase the safety of the mission, by being able to set a depth for over-depth triggered mission abort, at less than the minimum water depth in the survey area).

Figure 6 – Autosub6000 being recovered into its launch and recovery platform following its first deep survey mission. Note the EM2000 multibeam sonar mounted on the underside of the front section.

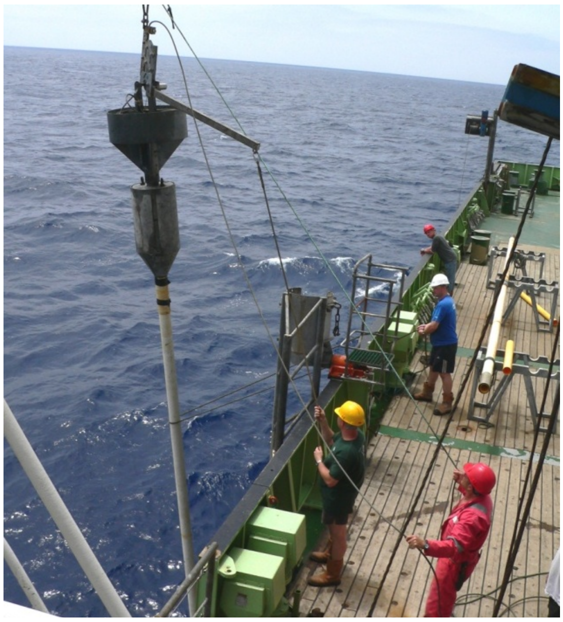

Figure 7 – A 10 m piston core being deployed while Autosub6000 is surveying an area of seafloor.

Following the dive, every mission included a stop, circling at 1000 m depth, and then again at 100 m less than the water depth while we checked the AUV engineering systems via the acoustic telemetry link. Only when we were content with the AUV performance did we send the command for it to continue. A risk analysis indicated that by doing this we could very significantly reduce the risk to the AUV due to system failure. The AUV descent rate was 0.9 ms^{-1}, taking 1.5 hours to reach the typical operating depth of 4600 m.

Following the descent, the vehicle executed a 1km box around the ship's position, while we gathered data for a range only navigation fix (Figure 8). The range only navigation was implemented in “near real time”, with the AUV self navigation telemetered back to the ship for each range we obtained to the AUV. Once the AUV navigation error had been calculated and quality checked (this took typically 5 minutes), the offset to the AUV navigation was sent via the acoustic downlink. We then sent the acoustic command for the vehicle to begin its survey. Typically, from launch to start of the survey took 3 hours. The survey underway, we were able to recover the tow fish used for communicating with the AUV, and the ship was free to carry out other operations, (usually to transit to another area and take piston cores - figure 7).

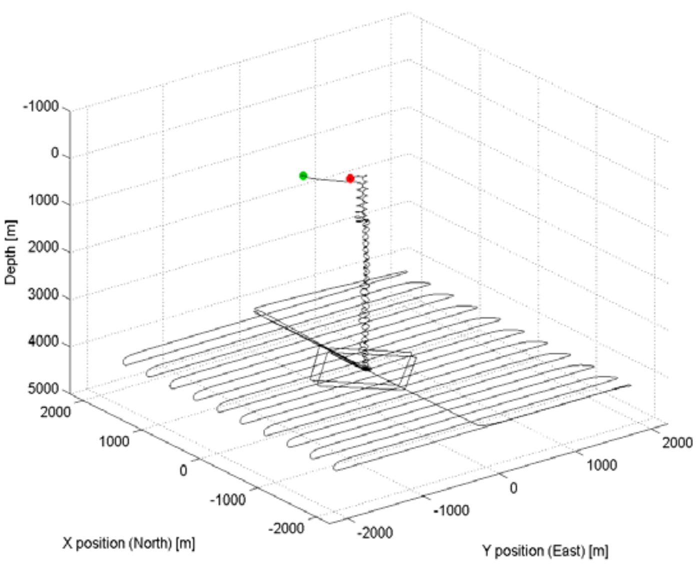

Figure 8 - 3D navigation trace for the first deep Autosub mission. Starting at the red dot. ending on green. Note the spiral for descent and ascent, the 1km boxes run at the start and the end of the mission, and the actual “lawnmower” survey run at 100 m altitude.

The AUV surveys took about 18 hours to execute. At the end of the survey, the AUV returned to the centre of the box and waited while circling at 100 m altitude (in case of unexpected delays with the other ships operations), waiting for our acoustic “continue” command. It then carried out another 1 km box around the ships position, for a post survey range only navigation fix.

After sending yet another acoustic command to the AUV, it began its ascent. For each mission we set the AUV to ascend at alternately high power and very low power, at a steep angle (60 degrees). The ascent rate at the low power is sensitive to the vehicle buoyancy, giving an accurate indication of any changes in buoyancy as the AUV ascends, and, more importantly, between missions. We did not detect any changes in buoyancy during the four missions of the cruise - a reassuring result. The average ascent rate was 1.5 ms^{-1}, taking 50 minutes to ascend from 4500 m.

With the USBL system still working with the AUV surfaced, it was generally easy to locate the AUV. Flashing lights and two UHF ARGOS transmitters on the vehicle were available, if necessary, to aid recovery. The engineering and multibeam data could then be downloaded from the vehicle via a WiFi link with an effective range of 500m.

For this cruise we experimented with compressed air powered grappling line launcher (manufactured by ResQmax) to recover the lines used for lifting Autosub into its launch and recovery. After some practice we found that this was a useful system, allowing us to reliably recover the AUV lines when it was floating significantly further from the ship than had been possible when using the traditional method of a crew member throwing the grappling line – an important improvement, as damage to the AUV through collision with the mother ship is a serious risk.

With the AUV safely recovered onto the ship, the next anxious wait was for the data to be processed. Had the system worked? After an hour we had our answer, and Autosub6000’s first bathymetric images (Figure 9).

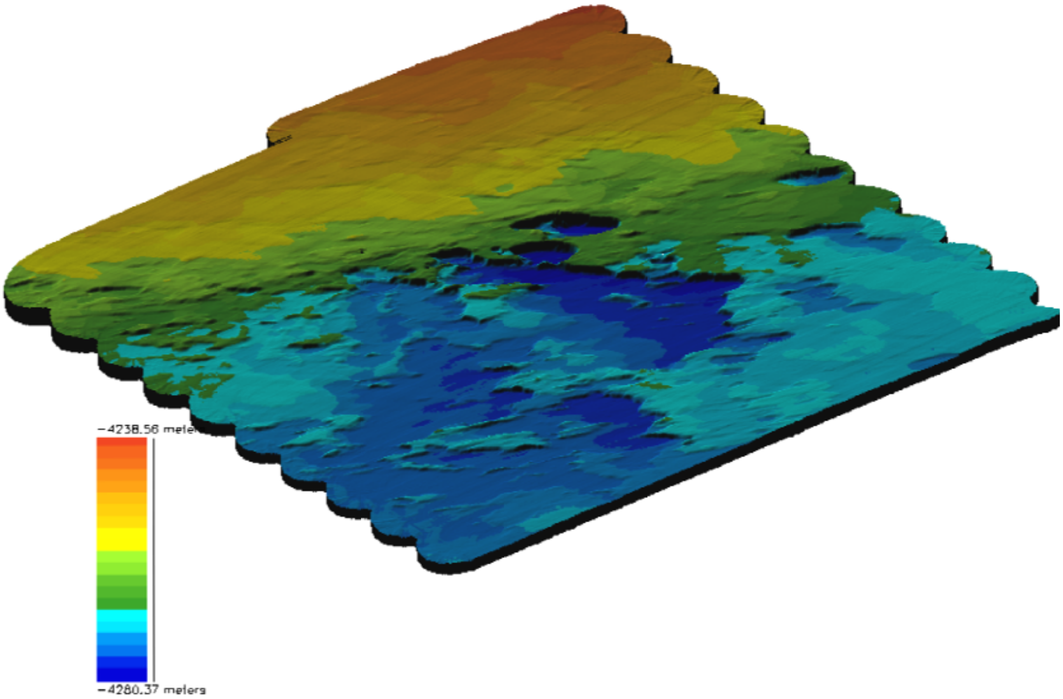

Figure 9 - First bathymetric survey image produced by the Autosub6000 system. A 4km x 4km survey of part of a submarine canyon, north of the Canary Islands. The scour marks, which are hundreds of metres across, were formed by turbulent submarine flows that ripped up huge volumes of seafloor sediment. Within a few hours of the recovery of the AUV, this image was used in helping to plan coring operations.

Image reproduced by permission of Dr Russell Wynn (NOC), principle scientist of RRS James Cook cruise 027.

Conclusions and Future Work

The trials in September 2007, and the science missions a year later were a success. The Autosub6000 AUV controlled, navigated and communicated as designed, and the batteries worked without any problems. The multibeam data was of good quality. The range-only navigation algorithms were tried and tested in both post processing mode, and during mission time. The results looked very promising as a solution to the initial positioning problem and as a way of estimating navigation drift during the mission. In the near future we will further develop our navigation algorithms, making use of the navigation and multibeam data recorded during the cruise.

Acknowledgments

Autosub6000 is being developed at the National Oceanography Centre, Southampton, with funding from the UK Natural Environment Research Council. We would like to thank the Master and crew of *RRS Discovery* cruise 323 and *RRS James Cook* cruise 027.

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