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1. Introduction

Using automated underwater vehicles (AUVs) to gather information on the marine environment is an attractive proposition. First, there is the issue of data coverage. For many purposes, the ocean interior cannot be sampled with sufficient spatial or temporal resolution using ships alone. Propelled sub-surface vehicles, such as Autosub, are able to undertake measurements along pre-programmed paths (Millard *et al.* 1998); although present limitations in cost-effective energy storage technology favour vehicles with ranges less than 1000 km. Nevertheless, many of the ideas and operating procedures for autonomous operation can be tested with the current generation of vehicles.

Secondly, AUVs can produce data of a higher quality and resolution that that obtainable from similar instruments on a surface ship or on a deep-towed sled. In part, the improvement is due to pure geometry: by operating closer to the sea bed, either at precise depths or altitude, the resolution is naturally higher; higher acoustic frequencies can be used; the AUV can follow a pre-programmed track far more accurately than a deep-towed vehicle, with less 'wastage' during turns.

Thirdly, automated vehicles can make measurements that would be far more difficult, or even impossible, to make from ships or other platforms. AUVs can be programmed to follow the bottom terrain, enabling measurements to be taken within the bottom boundary layer. Conversely, they can operate very close to the sea surface, offering a platform for measurements with far less unwanted motion than a surface vessel. In mid-water, AUVs can maintain depth accurately, or they can be programmed to follow density surfaces.

Fourthly, AUVs can obtain measurements from otherwise impenetrable environments, or where the presence of traditional platforms would disturb the environment. Plans are in hand for Autosub to explore the cavity beneath floating ice shelves of Antarctica and Greenland. With ice thickness increasing from 10's of metres at the seaward end to a kilometre and more at the root, the oceanographic, biological and geological conditions beneath these floating shelves have received little attention. AUVs can also contribute to studies of the ocean beneath sea ice. Although icebreakers can penetrate sea ice, they cannot measure sea ice thickness, neither can they make accurate assessments of parts of the ecosystem, as the vessel disturbs the environment.

In this paper we illustrate these four aspects of AUVs with reference to the missions carried out by the Autosub vehicles, designed, built and operated by the Southampton Oceanography Centre with major funding from the Natural Environment Research Council.

2. What measurements can we make today from Autosub?

Autosub is a large vehicle at 6.8 m long and 0.9 m in diameter. It can carry a payload volume of up to 1000 litres or up to 100 kg weight in water. Instruments can be carried either in the free-flooding nose or tail of the vehicle – the centre section is reserved for batteries and other key systems. This arrangement provides a flexible and adaptable space for scientists' requirements. It enables bulky sensors and instruments, some of them experimental and still rather ungainly, to be carried. This is a distinct advantage that a large AUV has over smaller, cheaper vehicles. Figure 1 shows some of the sensors and payloads that Autosub has carried during 1999 and 2000.

Much of the flexibility and benefits of an AUV emanate from the on-board vehicle control system. Autosub uses a sequential, event-driven mission management system (McPhail and Pebody 1998) that combines a simple approach to vehicle control with sufficient scope for different vehicle behaviours for gathering science data. As a rule, the vehicle will continue working towards a goal until the 'event' for that goal is reached, at which time the vehicle will work towards the next goal. A goal might be to reach a certain position or a certain depth, it might be to transit at a prescribed depth for such and such a period of time or it might be to dive until the altimeter reads a certain height above bottom. Nested 'if-then-else' actions are not possible with the current software.

Since April 1999 Autosub has been engaged in carrying out science research campaigns for projects comprising the NERC Autosub Science Missions thematic programme. The projects completed to date are shown in Table 1, with the number of missions in each campaign, the operating area, total track covered and the principal investigators and their institutions. Each campaign has required different instruments to be fitted to the vehicle, as discussed later in this section.

2.1 Physical measurements

Measurements of the basic physical variables of temperature, conductivity and pressure often form the core of an oceanographic data gathering exercise whether for physical, biological or chemical oceanographers. As a matter of course, Autosub carries two CTD systems with the sensors mounted on each side of the front part of the nose. While exposing the sensors in this way does involve some degree of risk from physical damage, mounting in an exposed position is essential to ensure data accuracy. Attempting to enclose the CT sensors within the nose cavity leads to errors due to the exchange of thermal energy with the surrounding trapped water, which is likely to be either warmer or colder than the sample. With care, temperature measurements accurate to better than .003˚C can be made. While all of the Autosub investigators to date have required CTD measurements, the campaign in the Strait of Sicily focused on the flow over the sill using CTD and ADCP data, concentrating on the flow close to the seabed.

When properly designed, AUVs provide a platform with very low vibration. This proves advantageous when making measurements of turbulence, for example using a pair of orthogonal shear probes. By making use of accelerometers to measure the (already low) vibration, signals on the shear probes from on-board sources such as the propeller and even the disk drive can be removed. It becomes feasible to measure kinetic energy dissipation rates down to 10^{-9} W kg^{-1}. Two campaigns have used two different turbulence measuring instruments: the study of physical processes in the upper ocean on *Terschelling* in March 2000 used an instrument described by Osborn (1985), while the Sicily campaign used a version by Dhanak and Holappa (1999).

Campaign	No. of Missions	Operating Area	Total Track km	Principal Investigators & Institutions
FRV *Scotia* July 1999	13	Northern North Sea	479 401 km unescorted	Paul Fernandes Marine Laboratory, Aberdeen Andrew Brierley British Antarctic Survey Mark Brandon Open University
RRS *Challenger* August 1999	7	Southern North Sea	466 316 km unescorted	Michael Collins Southampton Oceanography Centre George Voulgaris University of South Carolina
RV *Calanus* October 1999	13	Loch Etive Scotland	109	Julian Overnell & Kenneth Black Dunstaffnage Marine Laboratory Peter Statham & Chris German Southampton Oceanography Centre
MV *Terschelling* March 2000	9	Firth of Lorn Scotland	ca. 425 km over 380 km unescorted	Steve Thorpe Southampton Oceanography Centre Tom Osborn Johns Hopkins University
MV *Terschelling* April 2000	11	Loch Etive & Loch Fyne Scotland	ca. 150 km	as *Calanus* October 1999
RV *Urania* June 2000	4	Strait of Sicily	222 km	David Smeed Southampton Oceanography Centre Gian Pietro Gasparini CNR-IOF, Italy Manhar Dhanak Florida Atlantic University

Table 1 Summary of the 1999 & 2000 campaigns for the NERC Autosub Science Missions thematic programme. Prior to the start of the programme the vehicle had completed 1071 km during engineering and science trials.

2.2 Chemical measurements

Developing new *in situ* chemical sensors is an active research area. At present, only a small number of chemical species can be measured *in situ*. Of those that can be measured, most require wet-chemistry techniques that can prove to be problematical on AUVs because of long analysis times. Nevertheless, Autosub has carried optical-absorption and flow injection chemical sensors:

- The nitrate ion exhibits an absorption peak in the UV band near 210 nm that can form the basis of a fast-response (*ca*. 1 s) instrument ideal for use on an AUV. Unfortunately, the chloride ion absorption band overlaps most of that of nitrate, although there is sufficient distinction if the sensor can also estimate salinity to 0.1, Clayson (2000).

- Dissolved manganese can be measured by a flow injection wet analyser with a fairly rapid response time of about 20 s, Chin et al. (1992). Manganese concentration acts as an indicator of anoxia, and measurements from Autosub in two Scottish sea lochs during campaigns on *Calanus* and *Terschelling* have provided, for the first time, high spatial resolution profiles of this metal from near the seabed to the surface.

2.3 Acoustical measurements

Autosub has carried a number of acoustic instruments covering a wide range of frequencies:

- 250 kHz sidescan sonars for the study of acoustic backscatter from bubble clouds near the sea surface, with one sonar looking ahead of the vehicle and the other to the side. The sonars detect breaking waves; provide estimates of the vertical diffusion of momentum, through measuring the vertical decay of the backscatter; while variations in the amplitude of backscatter illustrate the presence of coherent structures such as Langmuir Cells, Thorpe (1985). These sonars were used successfully on the *Terschelling* campaign in the Firth of Lorn in March 2000.

- A broadband bubble resonator (Farmer 1998) was carried at the same time as the 250 kHz sidescan sonars and a turbulence probe on the *Terschelling* campaign. The resonator provided estimates of the air fraction between its discs (see Figure 1). By operating Autosub at various depths close to the sea surface, the vertical gradient of the air fraction could be determined and its horizontal variability studied under different wind and fetch conditions.

- A 38 kHz and 120 kHz EK500 fisheries echo sounder was fitted to Autosub in July 1999 for a campaign on the FRV *Scotia* to investigate hypotheses on fish avoidance of survey vessels, Fernandes *et al*. (2000). By using exactly the same sonar on Autosub as on *Scotia*, experiments could determine whether the acoustic fish biomass estimates from the very quiet Autosub were different from estimates made from *Scotia* while following Autosub at different layback distances. As reported by Fernandes *et al.* (2000) no difference could be found. Figure 2 is an echogram from Autosub taken using the 38 kHz sonar showing a herring shoal near the seabed.

- A variety of acoustic Doppler current sensors have been carried. As standard, the vehicle uses a 300 kHz Doppler profiler as a scientific instrument and as a bottom-track Doppler velocity log for navigation. The instrument combines a current profiling range of 100 m with a bottom track range of 200 m. Other instruments have included an upward-looking 300 kHz ADCP added for the Sicily campaign. Several sonars were added for the *Challenger* campaign in August 1999 to provide high resolution current profiles near the sea bed: a 1200 kHz downward-looking ADCP; a rapid-sampling (16 Hz) single-point acoustic current sensor and an experimental 1.75 MHz ping-to-ping coherent profiler with a sub-centimetre resolution, Voulgaris *et al.* (1999).

3. Where are these measurements taken?

The emphasis during both the Autosub development and operational programmes has been on matching the technical specification of the vehicle and its systems to the contemporary requirements of its users. There are a number of reasons for this approach. Firstly, it ensures that the vehicle development is closely coupled to the scientists' need; that is, the programme is 'science pull' rather than ‘technology push’. Secondly, it is usually more economic to design and procure systems only when their capability is needed. Of course, there are exceptions, where the more capable, more expensive, but nevertheless cost-effective solution has been used. The navigation sub-systems amply demonstrate this philosophy of specification matched to requirements.

The accuracy of position that is required to become associated with a measurement varies with the nature of the science to be undertaken. There is, in some cases, a need for accurate relative position, but less stringent absolute position. In general, wherever there is a need to return to a location, or where the location has specific properties that have been identified, there is a need for more accurate position fixing. Where the measured variables vary in time and space, then the absolute accuracy of location can often be relaxed.

Autosub’s routine primary navigation aid is GPS, either unaided or aided by differential corrections. This is a limitation, as navigation fixes can only be obtained on the surface. Sub-surface, the vehicle relies on dead reckoning using heading from a three component fluxgate magnetometer (a Seatex MRU-6) and speed from a 300 kHz acoustic Doppler log. If the vehicle altitude is less than 200 m, the speed measured is over ground, if the altitude is greater than 200 m, the speed is through the water. When running with bottom lock, the main limitation on the accuracy of dead reckoning is the heading-dependent calibration error of the magnetic heading sensor. With careful calibration, in the actual area of operation, heading errors from the magnetic sensor can be reduced to below 0.5˚, while the scale factor error for the acoustic log can be determined to about 0.1%. The best-case performance is seen in any regular survey pattern where the vehicle returns to its starting point, as this minimises the effect of acoustic log scale error and heading error (if the heading error is symmetric). For example, Figure 3 shows the track of mission 223 in the Firth of Lorn during April 2000. After five times around a closed square of 4.5 km a side (a total of 90 km) the position error was 220 m or 0.24% of distance travelled. In contrast, after a transit of 50 km to the northeast and seven sides of a 4.5 km square the error was 500 m or 1 % of the radial distance, equivalent to a 0.5˚ compass error.

Without bottom lock, the navigation error becomes dependent on the current. The easiest option at present is to surface more often for GPS fixes. Alternatively, if the vehicle operates in a relatively confined area, an acoustic positioning and telemetry system coupled with surface buoys with DGPS receivers can be used. Position fixes to an accuracy of better than 5 m can be sent to the vehicle, as described by Coudeville and Thomas (1998). Such a system was tested on Autosub in Portland Harbour in March 1998. If there is a need to operate over long distances such that acoustic positioning cannot be used, the only option is to improve the dead reckoning. Madsen and Bjerrum (2000) have reported impressive results using a Doppler-aided inertial navigation system on the Martin AUV. Future requirements for Autosub will lead to the addition of long-range Doppler logs (probably 75 kHz) and additional heading sensors.

5. Future applications

January 2001 will see Autosub operating under sea ice in the Antarctic near the South Orkneys, measuring the abundance and distribution of zooplankton in open waters and under sea ice, while also measuring ice thickness with the EK500 echo sounder. Later in 2001 the vehicle will be fitted with an experimental self-contained flow cytometer – an instrument to measure the characteristics of single-celled plants and particles using optical scattering and fluorescence.

In 2002 it is planned to begin a three-year programme of observations beneath polar ice shelves, beginning with investigations under the 79˚N glacier in Greenland before progressing to Antarctica. Several technical improvements to the navigation, collision avoidance and emergency abort systems will be needed before these campaigns. New sensors will also need to be added, including sidescan, bathymetric and sub-bottom profiling sonars.

6. Acknowledgements

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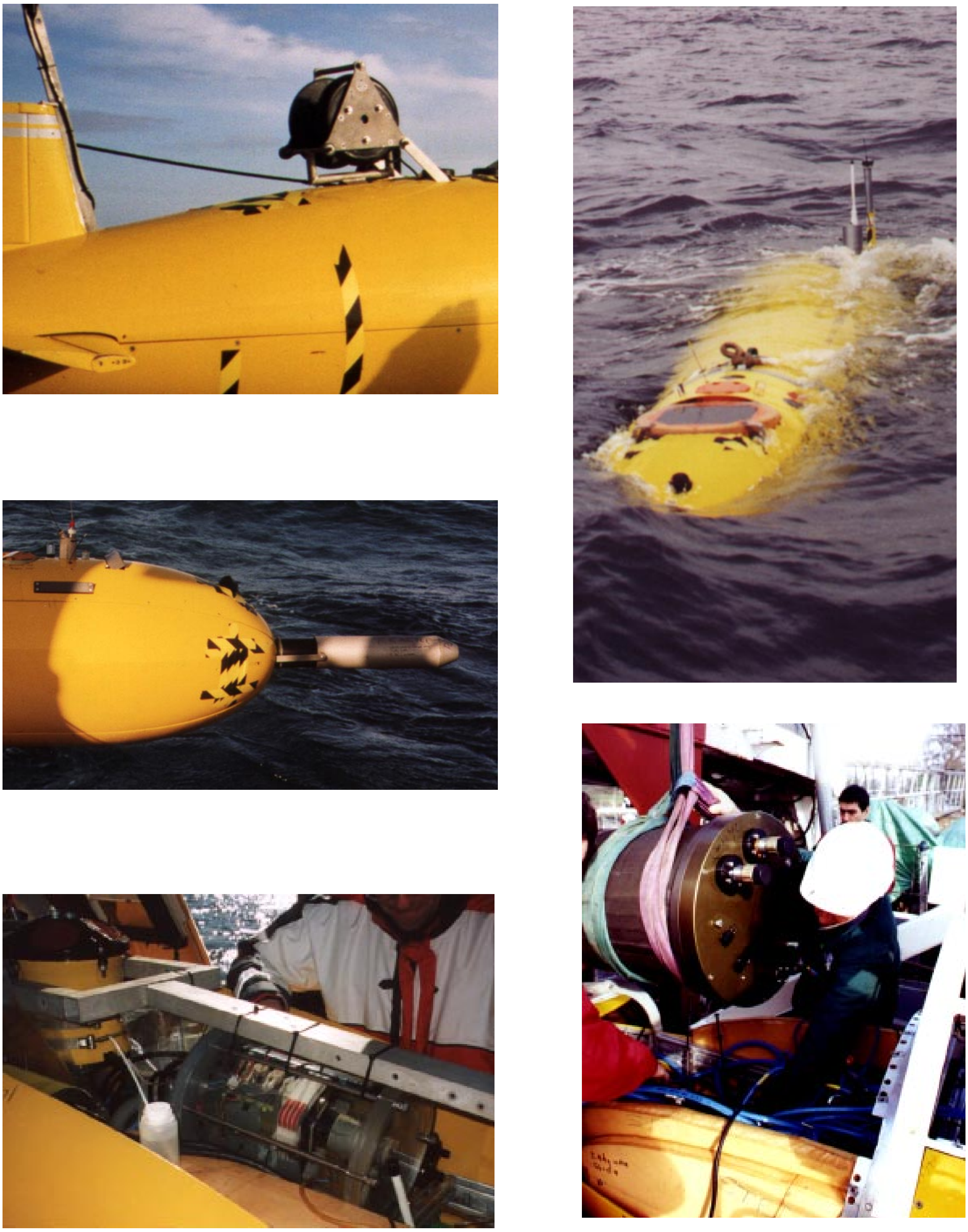

Figure 1 Several of the instruments and sensors that have been deployed on Autosub. Clockwise from top left: An acoustic bubble resonator, comprising two disc transducers, that measures the air fraction near the sea surface; acoustic transducers at 38 kHz (front) and 120 kHz (rear) connected to a EK500 scientific echo sounder; the instrument case for the EK500 being lowered into place within Autosub; a flow injection analysis system for the measurement of dissolved manganese; 250 kHz sidescan sonar transducers on the vehicle nose panels with a shear probe for measuring turbulence mounted in a protective sheath on the front of the vehicle.

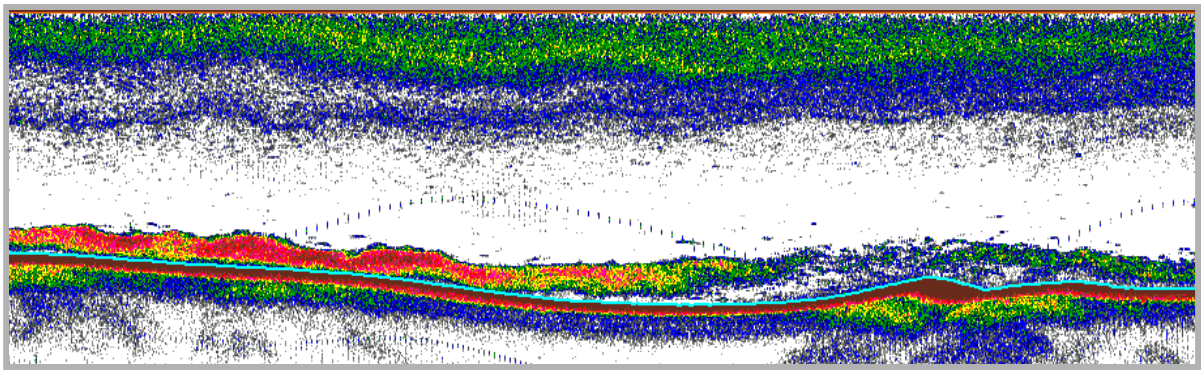

Figure 2 Echogram at 38 kHz from Autosub operating with FRV Scotia in the North Sea in July 1999.The vehicle was travelling at a depth of 15 m (top of the illustration), the sea bed, at a depth of about 100 m, can be seen as the continuous, thin continuous trace. Immediately above the bottom Autosub encountered a Herring shoal, initially with a high biomass but decreasing towards the right. The backscatter in the upper part of the water column was from zooplankton or micronekton, with internal waves present, as seen by the vertical modulation of the backscatter.

Mission 223 Navigation

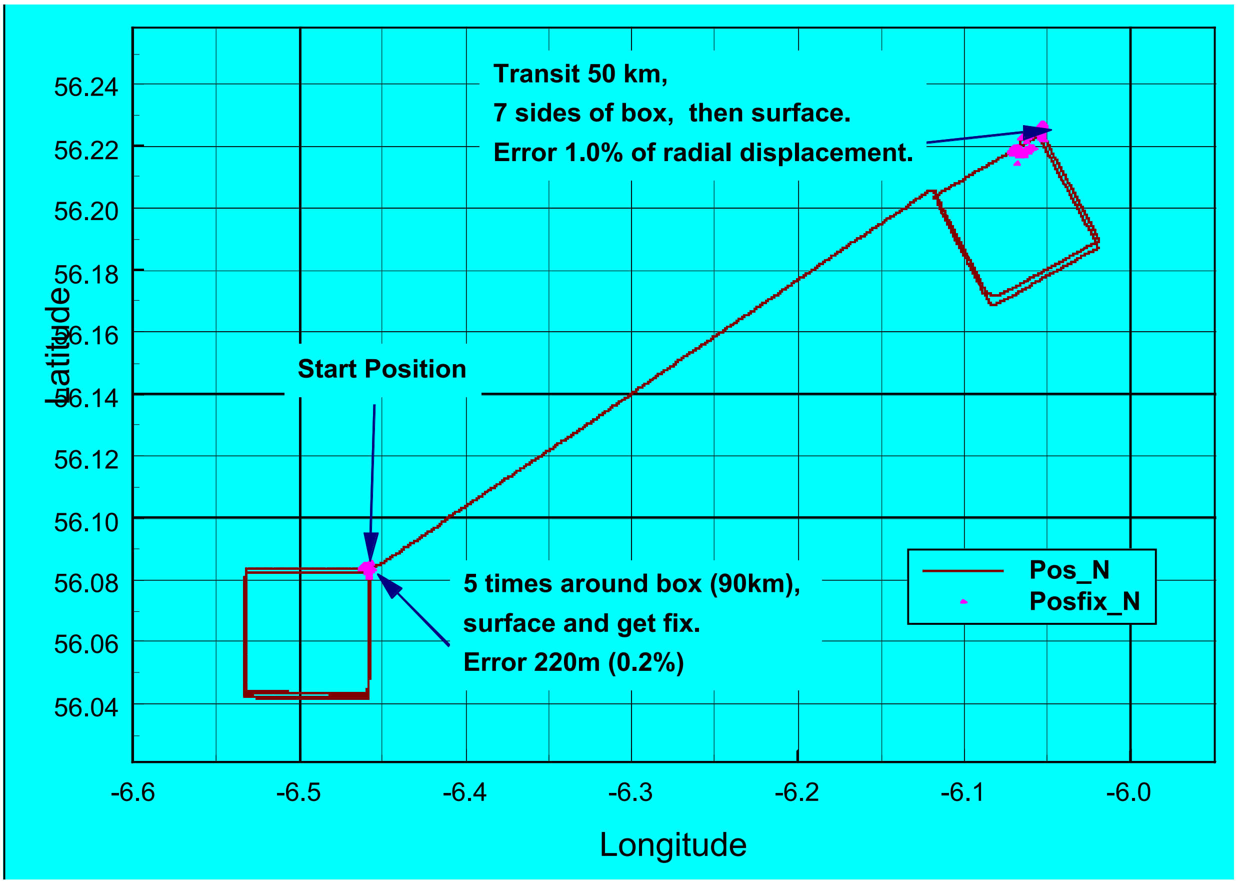

Figure 3 Navigation error during Mission 223 in April 2000, showing different error rates (as a function of distance travelled) for a small-scale closed box survey repeated five times (bottom left) and after a 50 km transit and partial completion of two closed boxes (upper right).