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Ocean robotics in support of fisheries research and management

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South Africa's small-pelagic fishery is a socio-economically important component of the country's commercial fisheries sector, second in value only to the demersal trawl fishery. Management of this sector relies on infrequent hydro-acoustic surveys, which provide measures of anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax* biomass used in the assessments of stock status and in the development of management plans for the sustainable utilisation of these resources. We demonstrate how technological capabilities in ocean robotics at the Council for Scientific and Industrial Research (CSIR) could augment the current resource-intensive hydro-acoustic ship-based survey programme and create opportunities for expanding its spatial and temporal resolution. We successfully implement and demonstrate an autonomous wave glider, fitted with a hydro-acoustic sensor and compare the data to a collocated 'traditional' ship-based acoustics survey. In the future these autonomous systems approaches could be seen as a means to lessen the cost burden of the ship-based survey, while at the same time with the added advantage of continuous collection over much wider spatial and temporal domains. This could enable a more reflexive stock management approach taking into account the seasonal characteristics of the fishery and its ecosystem. Gliders thus have potential to increase dramatically the quantity of information available to fisheries managers, thereby reducing uncertainty and contributing to improved management of valuable fish resources. They are likely to contribute to improved knowledge of the ecology of small pelagic fish species off the coast of South Africa in a changing climate and should potentially also permit the collection of biomass data for other marine resources currently not routinely monitored.

Keywords: acoustics, anchovy, echosounder, pelagic fish, sardine, Wave Glider®

Introduction

South Africa's exclusive economic zone (EEZ) extends over 1.5 million km^2 and includes the remote waters around the Prince Edward Islands in the Southern Ocean (Figure 1). Along with the benefits of this EEZ comes the enormous responsibility of managing its resources, which include its commercial fish stocks. The South African small-pelagic purse-seine fishery for anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax*, landing a total average catch of 350 000 tonnes (t) per annum over the past five years, is estimated to generate an income of more than R 1.5 billion per annum (South African rand; US\$1 = R 14.00; average exchange rate 2014), making it the second most valuable commercial fisheries sector after the demersal trawl fishery (R3.5 billion) (DAFF 2014; Hutchings et al. 2015). Despite the relatively small contribution of the fishing industry overall to South Africa's economy (1% of GDP), it is a crucial provider of employment and economic development to the coastal regions, particularly the region associated with the productive Benguela upwelling system on the West Coast (Hara et al. 2009; DAFF 2012). Of the roughly 27 000 individuals employed in the commercial sector, just more than 5 000 permanent and 3 500 seasonal job opportunities exist within the small-pelagic fishing sector (Hara et al. 2009; Hutchings et al. 2015). Many more individuals, including entire coastal communities, also depend on fisheries resources for food and as a means of securing their livelihood (Sauer et al. 2003; Hutchings et al. 2009; Cochrane et al. 2015). Ensuring that yields from fisheries resources are maintained or even increased through sustainable and responsible fisheries management and improved fishing efficiency is therefore in the best interests of South Africa.

Of key importance to managing commercially exploited resources is the level of scientific understanding of the ecology of key fish species and their population abundance and variability. The biomass of small-pelagic fish populations is known to fluctuate widely over space and time, driven primarily by recruitment variability and high natural mortality (Fréon et al. 2005). This, combined with their short lifespan and tendency to aggregate in patchily distributed dense schools, means that their assessment and management is often challenging (Barange et al. 2009). Traditional stock assessment methods employing population dynamics models to estimate stock size or indices based on catch

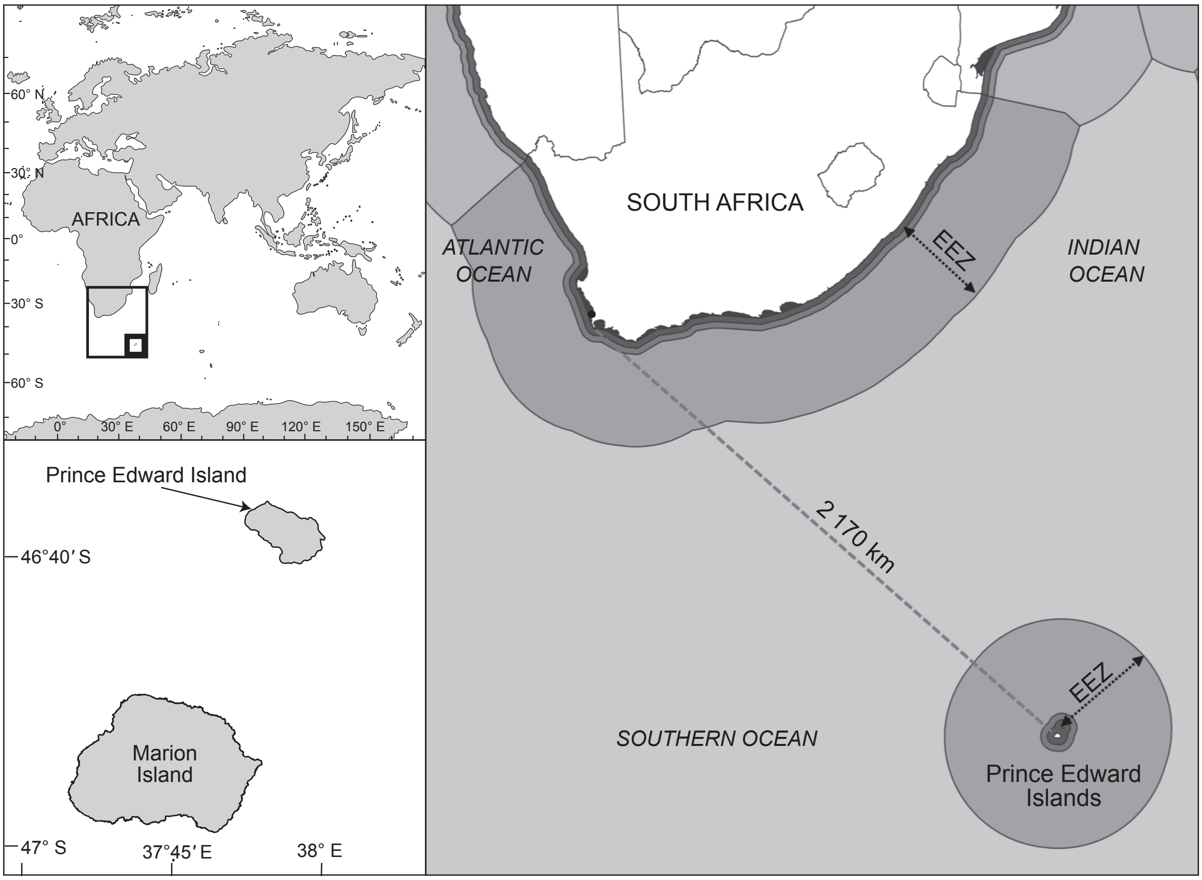

Figure 1: Map indicating the exclusive economic zone (EEZ) of South Africa, including its island territorial water associated with the Prince Edward Islands. South Africa's EEZ totals more than 1.5 million km^2

rates are of limited value, and instead extensive use is made of biomass indices derived from fishery-independent daily-egg-production or hydro-acoustic surveys (Gunderson 1993).

A programme of regular hydro-acoustic surveys to estimate the biomass of commercially important pelagic fish stocks was therefore established off the coast of South Africa in 1983 (Hampton 1987). This survey programme includes a recruitment survey in May/June (duration c. 40 ship days) and an adult biomass survey from mid-October to December (duration c. 55 ship days) each year (Barange et al. 1999; Coetzee et al. 2008; Shabangu et al. 2014). The adult summer surveys cover the entire area of the South African continental shelf between Hondeklip Bay on the West Coast and Port Alfred on the East Coast, whereas the sampling effort during recruitment surveys is concentrated mainly on the inshore areas of the shelf, but is extended northward to the Namibian border (Orange River mouth). The total length of the coastline sampled is therefore more than 1 000 km and the area surveyed during a typical adult biomass survey is approximately 165 000 km^2 (DAFF unpublished data).

To ensure sustainable small-pelagic fish resources, adaptive management is required because (i) the abundance of small pelagic fish can be difficult to quantify, given that they exhibit large natural variations in abundance over space and time, and (ii) small pelagic fish are prone to booms and busts, with large associated impacts on dependent organisms and the entire ecosystem (de Moor et al. 2011). The management of South Africa's small-pelagic fishery has evolved to become crucially dependent on the continued availability of data from these fishery-independent hydro-acoustic biomass surveys (Hampton 1992; Barange et al. 1999; Coetzee et al. 2008; de Moor and Butterworth 2009). They provide the primary inputs for stock assessments that estimate population parameters for operating models used in the development of harvest control rules for anchovy and sardine resources (De Oliveira and Butterworth 2004; de Moor et al. 2008; Barange et al. 2009). The annual survey estimates obtained are also key inputs into the operational management procedure (OMP) for calculating the next fishing season's total allowable catches (TACs) and total allowable bycatches (TABs).

Notwithstanding their importance for the management of pelagic fish resources, the high costs of undertaking these surveys limit the number of ship's days that can be made available, given budgetary restrictions. This places limits on survey effort or the degree of multiple sampling that can be obtained. This leads to knock-on effects on survey precision and accuracy, especially given the large area to be surveyed and the patchy nature of dense fish schools (Barange and Hampton 1997; Barange et al. 2005). There is also an ever-increasing demand for the limited ship time of the Department of Agriculture, Forestry and Fisheries (DAFF), with several commercially exploited resources being reliant on fishery-independent data for their assessment and management. Additionally, whereas the two annual hydro-acoustic surveys have to date been sufficient for ensuring sustainable utilisation of anchovy and sardine resources, they only provide information at short temporal scales. This necessitates fisheries scientists to draw inferences about fish behaviour, distribution and migration patterns during the intervening period between surveys – aspects likely to require a much clearer understanding, now that the sardine population is considered to consist of at least two stocks (de Moor and Butterworth 2015). The short observation window also limits the data available to investigate interactions between these fish resources, the fishery and the ever-changing marine ecosystem, and possible links with longer-term climate change.

Recent technological advances are seeing the marine research community participate in a new ocean-observing revolution. This is especially so given the increased presence and use of autonomous platforms, such as ocean-profiling floats, drifters and, more recently, ocean gliders (both deep and surface profiling) (e.g. Fernandes et al. 2003; Rudnick et al. 2004), as well as the enhancements in scientific sensor technology (Hart and Martinez 2006), particularly acoustic sensors. This has been prompted by the need to better understand our ever-changing environment, to increase our resilience to change and to ensure sustainable resource and ecosystem services exploitation. In South Africa, the use of ocean robotics has proven an extremely successful means to collect prolonged, high-resolution and continuous ocean-climate data from areas such as the Southern Ocean (Monteiro et al. 2015; Swart et al. 2015), Benguela upwelling system (M du Plessis et al., University of Cape Town, unpublished data) and Agulhas Current shelf regions (M Krug et al., Council for Scientific and Industrial Research [CSIR], unpublished data). These unprecedented ocean glider missions are highlighting the opportunities and benefits of using these unique platforms for scientific research, from the coastal domains to the remote open oceans.

We present an approach to either expand DAFF's current hydro-acoustic research programme or enable its long-term viability through cost savings by using autonomous ocean platforms, such as the Liquid Robotics Wave Glider® (https://www.liquid-robotics.com/). Here, we demonstrate the pioneering use of wave gliders in support of fisheries management in South African waters. The almost unlimited supply of wave and solar energy propel the platform and power on-board sensors, allowing them to be autonomous for several months at a time, while transmitting their data and being piloted in real time via satellite communications. We describe our approach to integrate fisheries acoustics sensors onto these gliders to provide fisheries biomass data. In the current study, a comparison is presented with near-simultaneous *in situ* ship- and glider-based fish biomass surveys. This demonstration expands the idea that data from gliders can be collected quasi-continuously over larger spatial domains, which should improve the temporal and spatial coverage of fish biomass surveys at a significantly reduced cost. We envision that this enhanced ecosystem observing paradigm will enable scientists to monitor more effectively the responses of fish stocks to environmental variability, resource exploitation pressure and climate change, and in so doing contribute to improved management of these valuable resources.

Material and methods

The Wave Glider

Wave gliders (WGs) are being used increasingly in a range of marine sciences and services within the surface ocean between the coastal and open ocean domains. This new generation of robotic oceangoing platforms provides an affordable and sustainable approach to data collection, enhancing the effectiveness of conventional observing platforms, such as ships, buoys and satellites. WGs are equipped with computers for navigation and payload control, satellite communication systems, and ocean sensors to observe the ocean environment around them. The power required to operate the sensors and computers is provided by solar panels, which are used to recharge lithium-ion batteries. Our study utilised the most recent version of WGs, called the SV3. The SV3 features technologies such as real-time on-board processing of large datasets, improved solar power and battery storage systems, and a larger payload capability.

The WG is steered by remote piloting via the Internet and can be programmed for autonomous operation. Continuous near real-time communication is provided via satellite (Iridium), cellular phone or radio links, which are used for piloting and data transmission. The platform does not require on-board power to propel itself, but rather harnesses wave energy for propulsion. The surface platform is connected via an umbilical cable to a submersible unit (subunit), located 4–8 m below the surface (depending on umbilical length options). It exploits the differential motion of passing waves between the surface platform and submersible. As waves lift the surface platform up, fins on the subunit propel the water behind the vessel. The fins are pushed to rotate in the opposite direction on the downward crest motion, whereas a rudder is used for steering. In the open ocean where there is substantial wave action, the WG could reach speeds of more than 2.5 knots (1.29 m s^{-1}), with the norm being between 1 and 2 knots. Solar panels installed on the surface float charge lithium-ion battery packs, which in turn power the glider's command and control system and all the sensors for observations. The use of these unlimited energy sources allows the WG to collect data and cover vast ocean domains for extended periods.

Acoustic integrated Wave Glider system (AWG)

Through a collaborative project between the CSIR, DAFF and Sea Technology Services, a custom-developed acoustic echosounder payload was designed for integration onto the SV3 WG, which is outrigged aft of the vehicle (Figure 2). The payload includes a 1 kW Simrad EK60 38 kHz GPT (general-purpose transducer), and a Simrad ES38-12 split-beam transducer, which collects high-resolution fisheries and benthic acoustic data. The payload is also supported

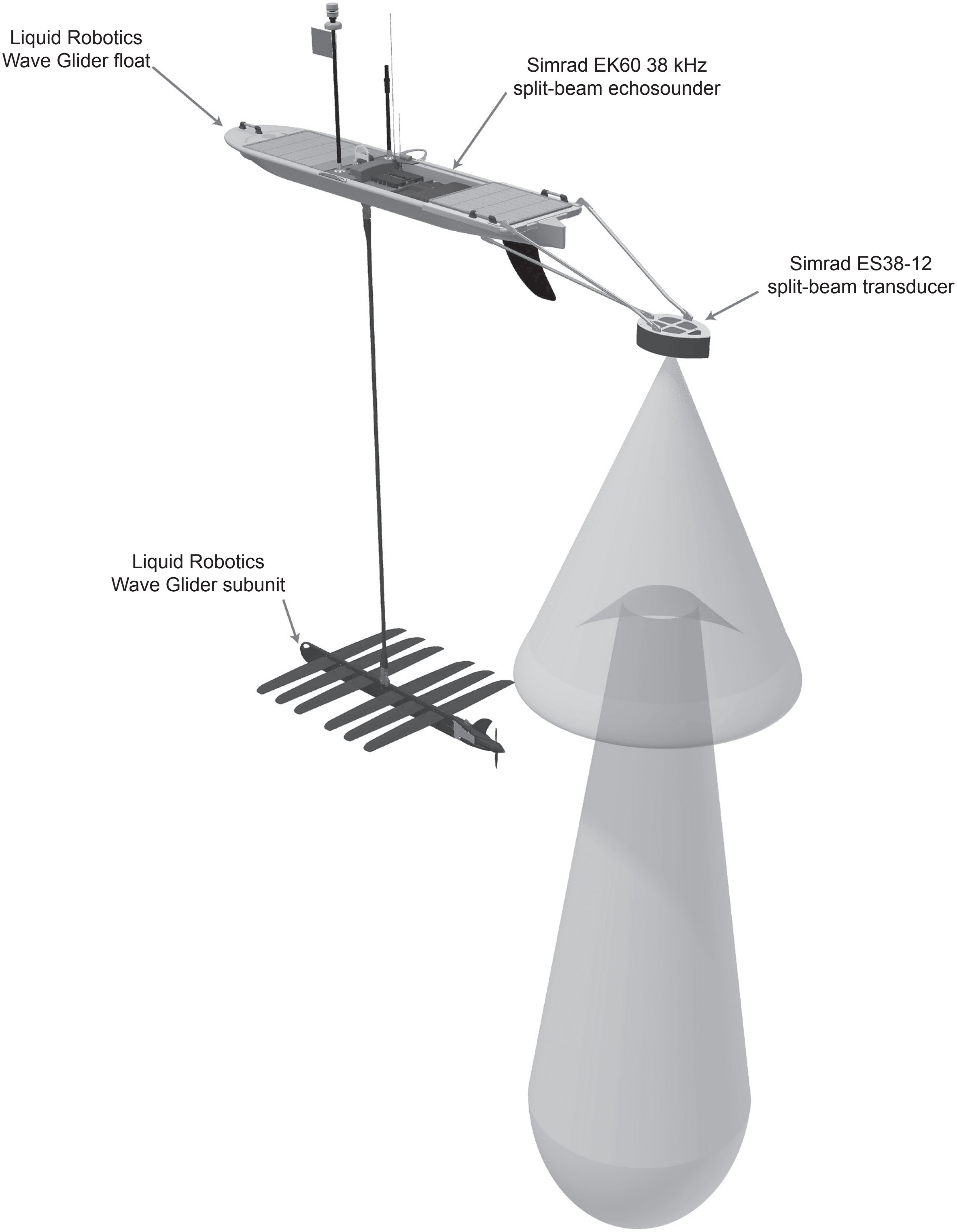

Figure 2: Assembly view of the acoustics payload integrated onto the Liquid Robotics SV3 Wave Glider. The acoustics transducer is located aft of the glider via a static gantry-style apparatus, which prevents the subsurface components of the glider interfering with the acoustics signal propagating through the water column

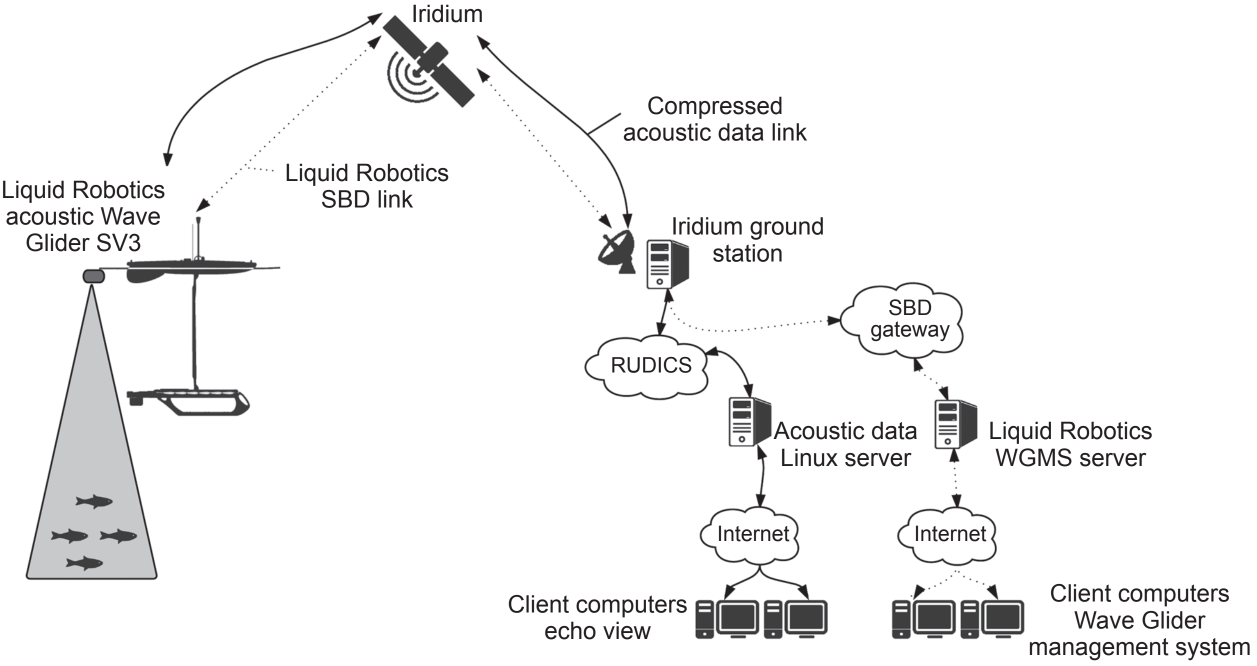

Figure 3: Conceptual acoustic integrated Wave Glider system (AWG) end-to-end data process: in-field acoustics data collection is relayed in real time via satellite communication systems to shore-side servers. Following this, appropriate data product processing occurs before the data are distributed to end-users through the Internet

with power and control circuitry and Iridium satellite telemetry hardware. To avoid interference of the sonar beam by the subunit, an aft outrigger bracket was developed to move the transducer's location out of the hull of the WG and place it behind the WG (Figure 2). High-resolution raw acoustic data files are stored on a solid-state drive aboard the WG. They are also bin-averaged and compressed by software running on the acoustic payload computer aboard the vehicle, before being transmitted to a shoreside server, via a dedicated payload Iridium modem and satellite link. Software on the shore-side server decompresses and verifies the bin-averaged acoustic data files and serves these to clients' computers via the Internet for analysis and presentation. Scientists, engineers and resource managers on land can use these data to monitor the performance of the echosounder and map the distribution of fish. Figure 3 provides the conceptual process, from data collection, real-time communication and data acquisition and eventually to product processing.

Ship-AWG dual deployments

A number of sea trials were conducted to test the echosounder integration with the AWG, with a total of 45 days at sea completing various transects between the inshore and offshore areas off South Africa's west and south coasts, as well as off Dassen and Robben islands. These initial trials allowed us to optimise the performance of the system and troubleshoot engineering or data issues common with these forms of integrations, and to identify potential caveats to the platform's ability to deal with environmental conditions, such as strong currents that frequent South Africa's ocean domains. In addition, they demonstrated that the AWG is capable of following stipulated survey tracks accurately.

The performance of the AWG, as well as the scope to integrate it into the hydro-acoustic biomass-survey programme, was tested between 30 October and 5 November 2015. The AWG deployment was timed to coincide with the routine pelagic biomass survey being conducted by the FV *Compass Challenger*. This 57-m long, 840 t commercial trawler, owned by the Oceana Group, had been used by DAFF in a number of prior acoustic surveys, because of ongoing operational problems with its own research ships. After consideration of prevailing current conditions and differences between the survey speeds of the FV *Compass Challenger* and the AWG, a c. 120 nautical mile section of the research vessel's planned survey grid in the nearshore area between Cape Point and Danger Point on the South Coast was selected for surveying by the AWG and preprogrammed into its navigation system (Figure 4).

The Simrad EK60 echosounder system on board the WG was calibrated on 14 October 2015 according to standard reference sphere methods (Foote et al. 1983) using the Simrad lobe calibration program. Calibration settings, however, were not downloaded to the system prior to the survey and the survey was conducted using default settings (gain 21.5 dB; S_A correction factor [CF] = 0.0 dB). These settings were updated, based on post-processing of the calibration data in the Myriax Echoview software, prior to data analyses (gain 21.43 dB; S_A CF = –0.69 dB). The EK60 ES38B system on board the FV *Compass Challenger* was similarly calibrated on 20 October 2015.

The intention of this deployment was not to conduct a

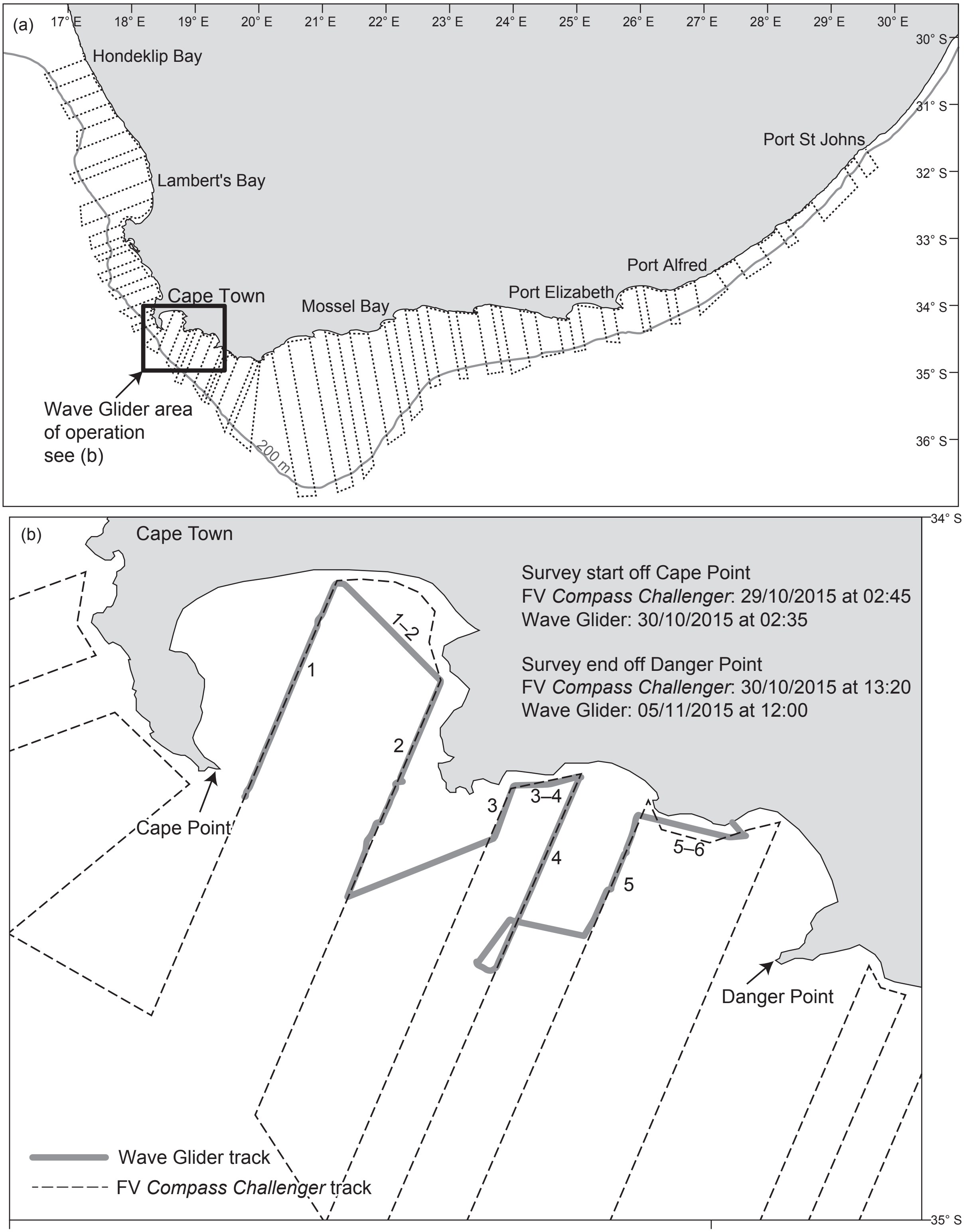

Figure 4: (a) The design of the pelagic biomass survey completed by the FV *Compass Challenger* between 19 October and 2 December 2015, and (b) the sections (numbered) of the original survey track completed by the Wave Glider and retained for comparison with results from the survey vessel

typical acoustic intercalibration, because the timeframes of sampling the same region were very different between the ship and the Wave Glider – the ship was able to survey transects at c. 10 knots, whereas the Wave Glider speed ranged between 1 and 2 knots. Given this difference and the fact that fish behaviour and movement changes rapidly (Misund et al. 2003), a direct comparison between the platforms is not possible. Nonetheless, several features of the AWG and its on-board acoustic system were investigated and deemed important for integration into the existing DAFF hydro-acoustic survey programme, including: (i) broad comparisons of fish density estimates obtained between the acoustic systems, with a focus on the differences in the surface blind zone; (ii) the level of aeration and depth of the bubble layer below the AWG acoustic transducer during different sea states; (iii) the level of detection of the subunit in the acoustic beam and its influence on fish density estimates; (iv) the ability of the AWG to follow a predetermined survey track; (v) the average speed of the AWG under different weather conditions; and (vi) the capacity of the solar panel power supply to cope with continuous day and night operation.

Analyses of the acoustic data were performed with Myriax Echoview. To enable broad comparisons of relative fish density estimates obtained from the two survey platforms, transects were integrated over 0.1 nautical mile elementary sampling distance units (ESDUs) between the surface blind zone and a distance of 0.5 m (back-step) off the sounder-detected bottom at a minimum Sv threshold of −65 dB. Mean nautical area backscattering coefficient (NASC; m^2 nautical mile^{-2}) values obtained per 0.1 nautical mile ESDU were then averaged per transect and for the whole survey area according to the method of Jolly and Hampton (1990).

On the AWG, the Simrad ES38-12 transducer was outrigged 1.5 m aft of the platform at a depth of 0.5 m below the water surface. The transition zone between the near field and far field of this transducer was typically at a range of approximately 1 m, but, in the case of this particular transducer, the transmission pulse extended to a range of 3 m, resulting in an effective sampling start depth below the surface of 3.5 m. On the FV *Compass Challenger*, the Simrad ES38B transducer was hull mounted at a depth of 4.5 m below the water surface. Given the larger size of this transducer, the near field extended to approximately 3.5 m, resulting in an effective sampling start depth of 8 m. Fish distributed between 3.5 m and 8 m depth would therefore be detected only by the WG's acoustic system and this might potentially result in lower densities being observed by the acoustic system on board the trawler. To check the influence of surface fish distribution on the comparability of data collected from the two platforms, data from the AWG system were therefore reintegrated with an effective start depth of 8 m.

Whereas the shallow depth of the AWG's transducer potentially allows for estimation of fish density close to the surface, aeration close to the surface during bad weather could compromise the quality of the data collected. Bubbles driven below the surface and over the face of the transducer could result in strong attenuation of the acoustic signal and even result in ping loss (Dalen and Løvik 1981; Simmonds and MacLennan 2005). The maximum depth of the bubble layer was selected manually for each ping and the NASC between the effective start depth (3.5 m) and the bottom of the bubble layer was compared at different wind speeds and for different wind directions relative to the direction that the Wave Glider was moving.

Two distinct low-density bands, or layers, originating from detection of the subunit in the transducer side lobes at a depth of 5–6.5 m and 9.5–11 m, were visible on the echogram produced from the AWG acoustic data. The level of detection of the subunit within the acoustic beam and its influence on density estimates was quantified by setting two narrow horizontal regions across the echogram. A 5.5 nautical mile section of transect was selected, comprising 3 900 pings for which no surface aeration or fish targets within the upper 15 m of the water column were apparent. The frequency distribution of pixel Sv values falling within the two horizontal regions was evaluated relative to the minimum integration Sv (−65 dB) threshold, and NASC values from integrations performed over five-ping intervals over the entire water column were contrasted with NASC values obtained from within these bands.

Results

The sections of transects surveyed by both the AWG and the FV *Compass Challenger* and the time-frames associated with starting and ending the joint part of the survey are shown in Figure 4b. The AWG was not able to sample more than approximately 15 nautical miles offshore and had to be diverted inshore on two occasions when it encountered strong current associated with the Good Hope jet, a local, strong and quasi-permanent current flowing in a north-westerly direction in excess of two knots. Additionally, whereas the FV *Compass Challenger* surveyed the entire area, including offshore extensions to the shelf edge in just more than 34 hours, the AWG completed the designated survey in six days.

The average speed of the Wave Glider over the course of its deployment was 1.36 knots (SD 0.36, maximum 2.21, Figure 5a), with a linear increase in AWG speed with wind speed (Figure 5b) and the fastest AWG speeds generally being reached when the wind was on the stern, starboard quarter or starboard beam (Figure 5c). These increases in WG speed likely resulted from enhanced swell size providing increased potential energy to the WG subunit, as well as windage on the surface float.

The depth of the surface bubble layer (also the depth at which integration started, or the surface exclusion depth) for the AWG acoustic system typically ranged between 4 and 6 m, but extended to more than 8 m for 37% of the ESDUs (Figure 6a). The surface exclusion depth for the FV *Compass Challenger* was typically 8 or 9 m, extending to 10 m on a few occasions. The shallow (<5 m) integration start depth coincided with low to moderate wind conditions (<9 knots) and increased to 8 or 9 m at wind speeds in excess of 9 knots (Figure 6b). The NASC of the bubble layer increased rapidly with wind speeds >12 knots and an increased vertical extent of the bubble layer coincided with an increased mean NASC of the bubble layer ($r = 0.91$, Figure 6b), suggesting that at high wind speeds integration results will not only be negatively biased, because of signal attenuation within the deepening bubble layer, but that fish

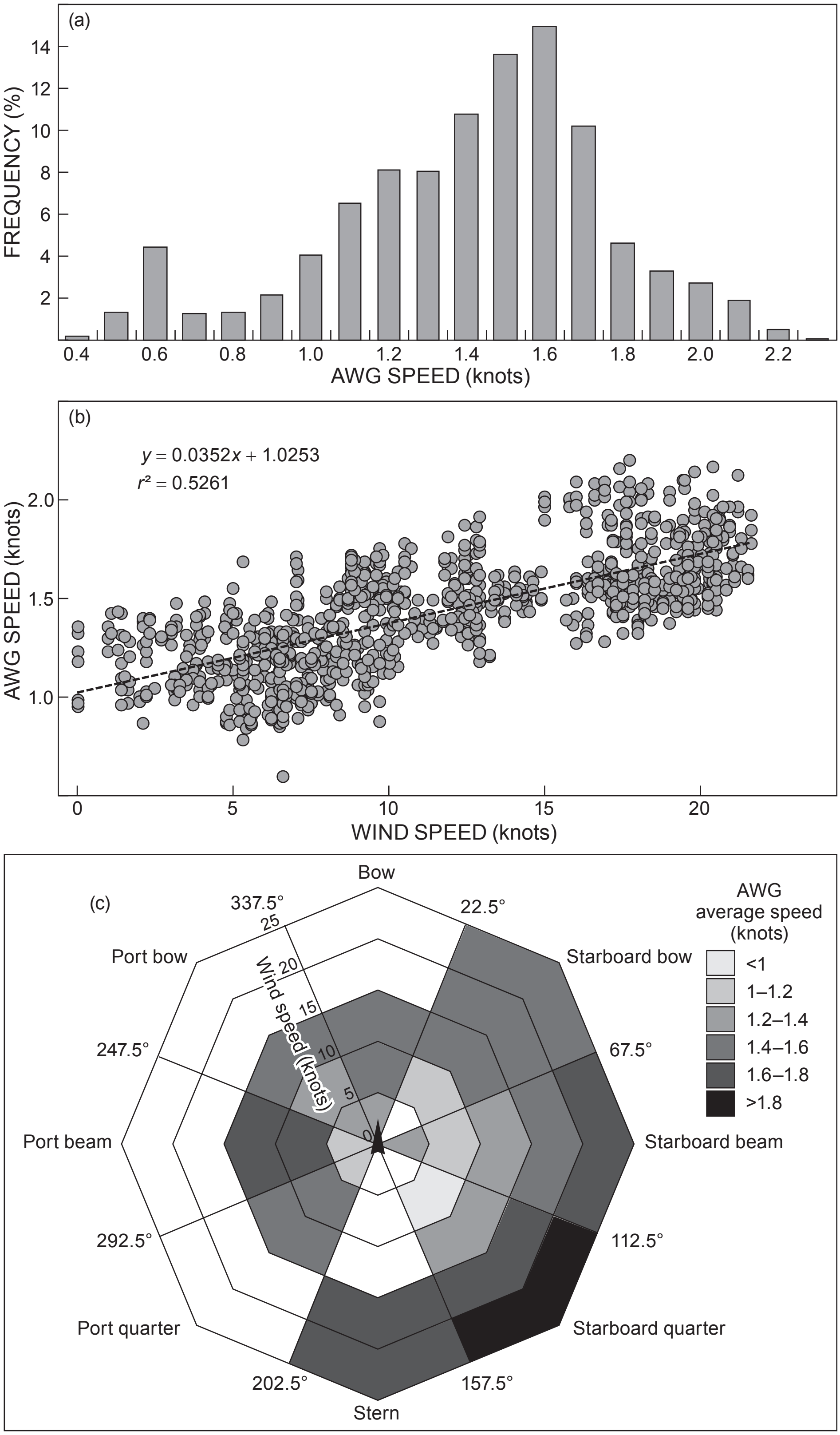

Figure 5: (a) Frequency distribution of the speed (averaged over 0.1 nautical mile ESDU) attained by the Wave Glider, (b) the relationship between average speed attained by the Wave Glider and true wind speed measured by the on-board weather station for each ESDU and (c) a rose diagram representing the influence of wind speed and direction relative to Wave Glider heading on the speed attained by the glider

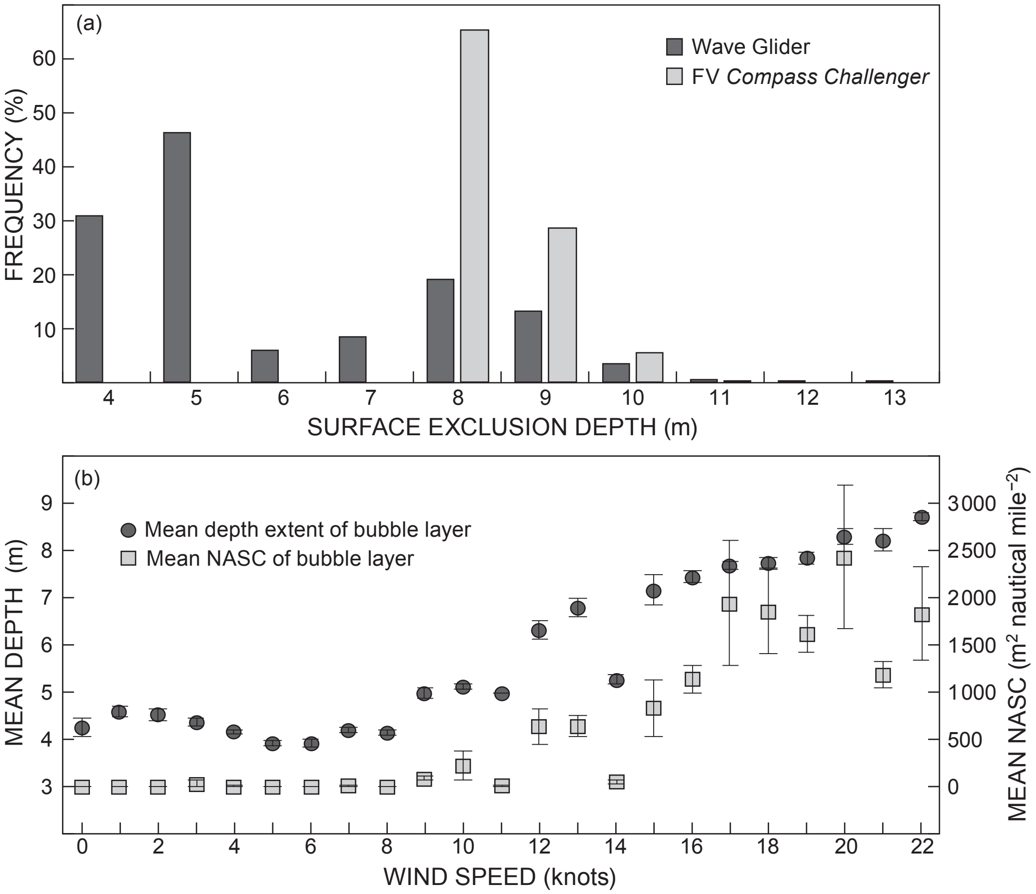

Figure 6: (a) Integration start depth frequency (%) for the AWG and the FV *Compass Challenger* over all ESDUs and (b) the mean depth of the surface bubble layer and its associated mean S_A (NASC) for increasing wind speed classes. Vertical bars represent SE

occurring close to the surface (<7 m) will be masked by the bubble layer and will not be detected by the acoustic system on the AWG. No strong directional response of wind on the depth of the bubble layer was evident from our data, with the mean depth of the bubble layer generally increasing with increasing wind, irrespective of direction.

The level of detection of the subunit or fin in the side-lobes of the Simrad ES38-12 transducer was low (Figure 7a) with >93% of all Sv values, in both subunit echo layers, falling below the minimum integration threshold (−65 dB) and <3% of Sv values exceeding −60 dB. The average NASC (over five-ping intervals) attributed to the subunit was 1.06 m^2 nautical mile^{-2}, ranging from 0 to 10.09 m^2 nautical mile^{-2} (Figure 7b), and in 65% of the intervals contributed <1% to the total NASC of the water column. The larger percentage contributions to the total NASC coincided with intervals containing very few or no fish targets.

The mean NASC per 0.1 nautical mile ESDU varied greatly between the acoustic sampling platforms (Figure 8) and between transects for each of the platforms. However, despite this fine-scale variability, the frequency distributions of NASC and mean NASC recorded by each of the acoustic systems per ESDU were comparable (Figure 9; two-sample $t_{(1\,730)} = -0.68$, $p = 0.49$). The transect-derived survey mean NASC and its coefficient of variation (CV) were also not significantly different (Table 1; two-sample $z = -0.08$, $p = 0.94$). The mean NASC measured by the AWG (2 370.2 m^2 nautical mile^{-2}, CV = 0.336) decreased by only 3.3% when a deeper surface exclusion zone, comparable to the 8 m blind surface zone of the FV *Compass Challenger*, was used. The only notable difference was observed during the inshore transit between Transects 1 and 2, where a very dense layer of scattered fish was detected by the Wave Glider very close to the surface.

Discussion

Earlier tests conducted in March 2015 had confirmed that the binned and compressed AWG acoustic data transmitted ashore via satellite and then decompressed were virtually identical to the raw data stored on board the WG. The transmitted EK5 datagram closely resembled the raw data echogram and all echo traces between the surface and first bottom echo were identical at a threshold of −65 dB, the agreed minimum for transmission. The transmitted file contained all the necessary parameters to ensure compatibility with current processing and integration software (Myriax Echoview). Additionally, the GPS data transmitted were sufficient to allow for plotting the surveyed track, for synchronisation of each ping with its position on the track

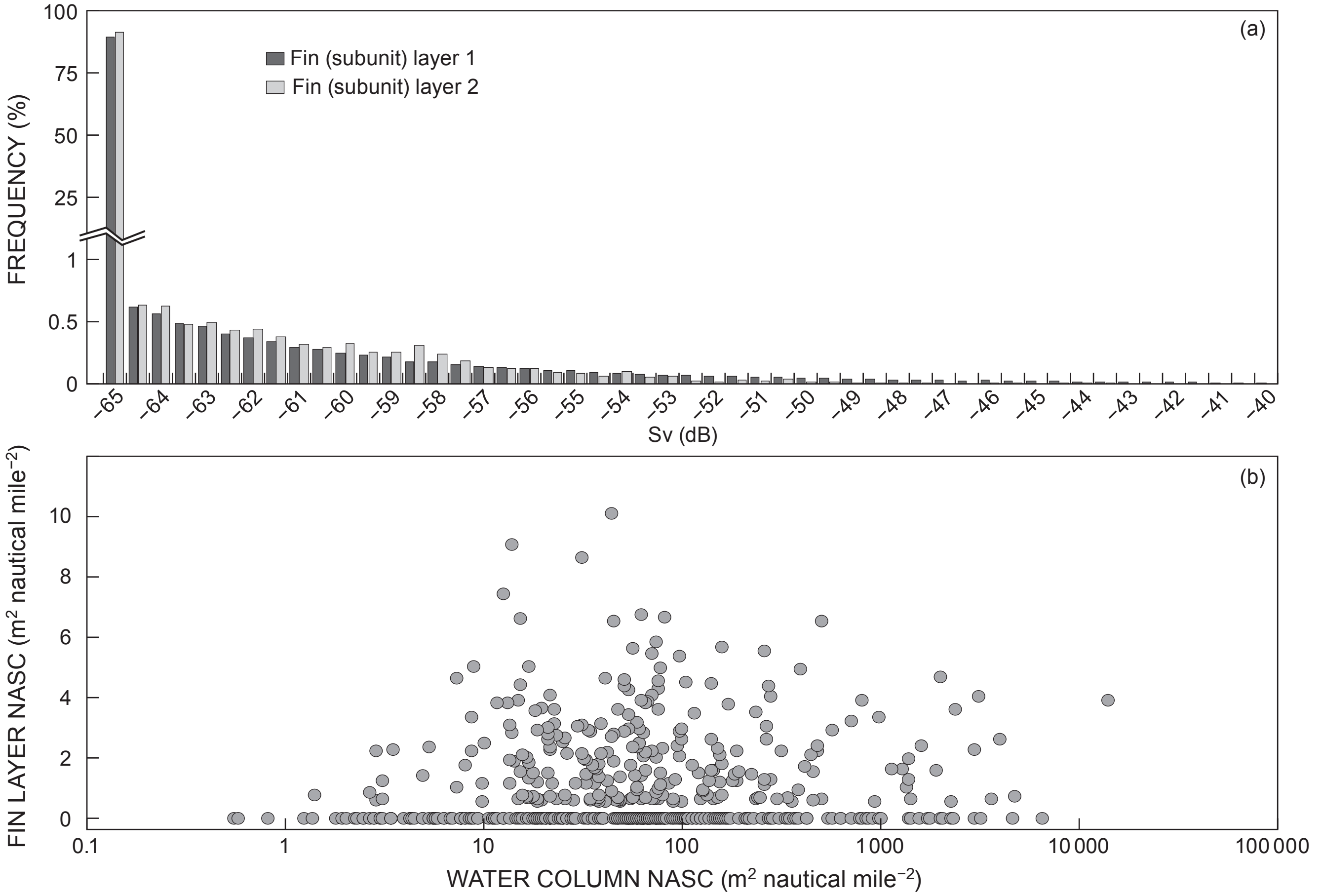

Figure 7: (a) Frequency distribution of pixel Sv values obtained from two layers (subunit or fin layer 1, 5–6.5 m depth; subunit or fin layer 2, 9.5–11 m depth) over a 5.5 nautical mile section of transect and representing backscatter attributed to the subunit being detected in the side lobes of the 38-12 transducer, and (b) a comparison of the summed NASC emanating from within these two layers with the NASC measured over five-ping intervals throughout the water column for the 5.5 nautical mile section of transect

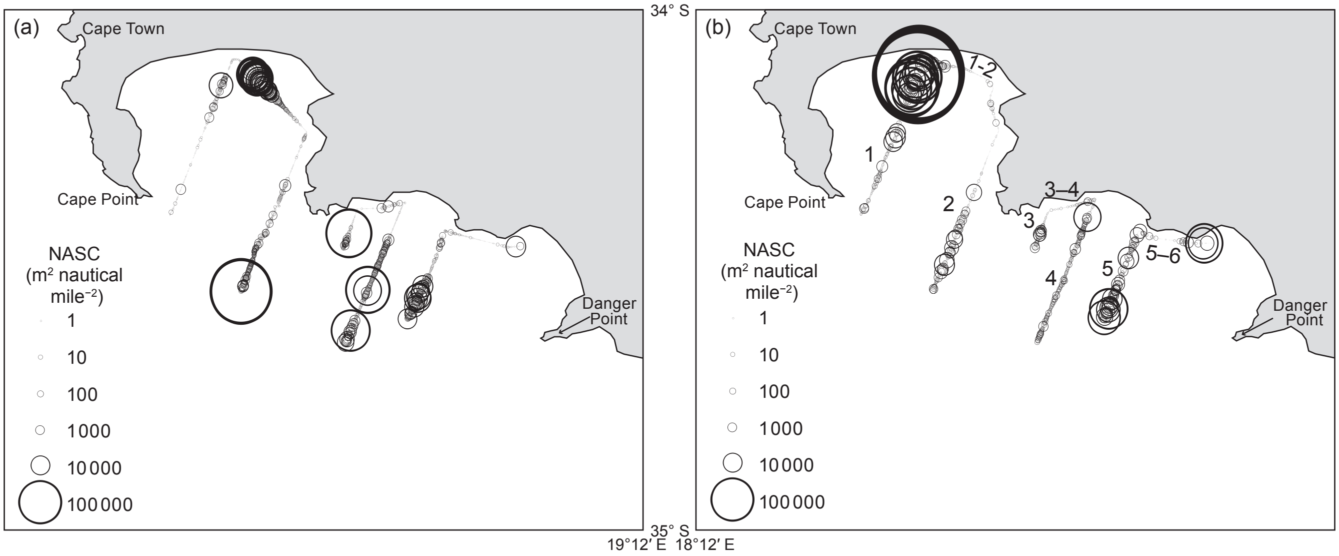

Figure 8: Mean NASC measured for each 0.1 nautical mile ESDU by the acoustic systems of (a) the Wave Glider and (b) the FV *Compass Challenger*. The size of each circle is scaled proportional to the square root of the NASC measured. Survey track sections (transects) are numbered

and for delineation of integration cells and measurement of fish school dimensions. Integration (NASC) of acoustic backscattering data from these data and the original raw data file logged on board the AWG agreed to within 0.5%, the small difference being attributed to the number of decimal places of binned Sv values transmitted. It was also confirmed that all analyses routinely carried out during a pelagic fish acoustic survey could be performed on the transmitted datagram file, i.e. integration, export, bottom pick, school detection, etc., and consequently, even in the event of long-term deployments of the AWG, the datagrams sent ashore in real time would enable immediate analyses of fish biomass and behaviour.

Mean density estimates of pelagic fish are typically influenced by the 'hit or miss' of large schools, which typically contain the largest proportion of the biomass (Marchal and Petitgas 1993; Petitgas 1993). Schools of pelagic fish in the southern Benguela have also been shown to be highly dynamic, with frequent inter- and intraschool events (Misund et al. 2003) and sustained swimming speeds in excess of 0.5 m s^{-1}. Given the time lapse between sampling the same sections of survey transects, the differences in time of day that each of the transect sections were surveyed, differences in survey speed and accuracy of navigation, and inherent patchiness of fish aggregations and their dynamic behaviour (Gerlotto and Petitgas 1991; Fréon et al. 1993, 1996; Fréon and Misund 1999; Coetzee et al. 2001), it was not expected that the AWG and survey vessel would have encountered the same fish densities and hence direct comparisons of fish densities are not always appropriate for testing comparability of acoustic systems. It is therefore not unexpected that densities measured between the two acoustic systems varied substantially at fine scale. What is promising, however, is the large-scale comparability of the mean estimates obtained, despite a considerable time lapse between surveying by the FV *Compass Challenger* and the AWG.

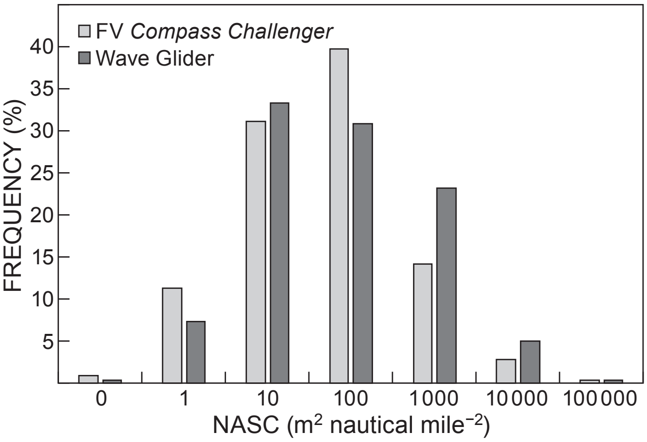

Figure 9: Frequency distribution of NASC measured for each 0.1 nautical mile ESDU by the acoustic systems of the Wave Glider and the FV *Compass Challenger*. Note the logarithmic scale on the *x*-axis

Differences in fish shoaling behaviour and level of aggregation between day- and night-time periods will affect the detectability of fish, as well as the relative density of fish aggregations over small spatial scales. Small pelagic fish are known to form small, isolated and very dense schools during the day, whereas at night they disaggregate closer to the surface in widely distributed layers (e.g. Blaxter and Holliday 1963). Despite these differences at small spatial scales, survey estimates are unlikely to be biased by fish aggregating behaviour unless a large portion of the fish biomass is located in the surface blind zone at night, or avoidance reactions to a survey vessel are heightened during the day. There was no evidence for either of these attributes during this survey, although admittedly detecting avoidance effects is difficult.

Although there were no large apparent differences in mean density measured by the AWG for different surface exclusion depths, the fact that the majority of integrations were performed from a depth of 4 to 5 m below the surface, despite the adverse weather conditions, is a significant advantage for night-time surveying where pelagic fish might at times go undetected close to the surface. The deeper extent of the bubble layer on a few occasions, indicating substantial attenuation of the acoustic signal, is not really of consequence, because surveys are typically temporarily

Table 1: Mean nautical area back-scattering coefficient (NASC), variance (var.) and coefficient of variation (CV) measured by the FV *Compass Challenger* and the Wave Glider for each of the surveyed transects (including sections between transects), as well as for the total survey area. Also shown is the transect length and the comparison of NASC estimated by the Wave Glider when a surface exclusion depth of 8 m (typical for the survey vessel) was used rather than a shallower surface exclusion zone of typically 4–5 m

	FV *Compass Challenger*				Wave Glider				Wave Glider with 8 m depth surface exclusion			
Transect	NASC (m^2 nautical $mile^{-2}$)	Transect length (nautical miles	Var.	CV	NASC (m^2 nautical $mile^{-2}$)	Transect length (nautical miles)	Var.	CV	NASC (m^2 nautical $mile^{-2}$)	Transect length (nautical miles)	Var.	CV
1	7 428.2	18.1	15 979.3	0.017	448.7	23.4	184 872.9	0.958	448.7	23.4	172 347.2	0.925
2	574.3	19.4	153 541.2	0.682	1 489.8	27.1	198 595.6	0.299	1 488.2	27.1	183 658.7	0.288
3	759.4	4.9	10 581.7	0.135	2 169.0	7.5	18 229.0	0.062	2 169.0	7.5	16 968.9	0.060
4	640.1	17.5	124 859.8	0.552	2 579.3	19.8	97 288.9	0.121	2 579.3	19.8	89 623.2	0.116
5	2 316.8	11.1	42 792.1	0.089	3 242.0	13.6	48 565.3	0.068	3 242.0	13.6	44 843.0	0.065
1–2	287.7	13.3	77 874.9	0.970	8 434.8	15.1	26 708.2	0.019	7 788.6	15.1	26 694.3	0.021
3–4	150.8	4.7	10 037.2	0.664	290.5	6.8	16 562.0	0.443	290.5	6.8	15 472.1	0.428
5–6	1 165.2	7.6	24 139.1	0.133	289.5	11.1	43 758.6	0.723	289.5	11.1	40 866.8	0.698
Survey	2 066.5	96.6	459 805.1	0.328	2 370.2	124.4	634 580.5	0.336	2 291.4	124.4	590 474.1	0.335

halted when excessive aeration occurs below the hull of the ship. A similar approach can be followed with the AWG, whereby it is put into a holding pattern until conditions improve. Alternatively, there is the option of towing the acoustic transducer at depth behind a wave glider (Greene et al. 2014).

The AWG's ability to be piloted and to achieve survey objectives by following way points was successfully demonstrated (Figure 4). The adherence of the Wave Glider to the predetermined survey track was very good, despite strong north-westerly currents and adverse wind and sea conditions during much of the survey period. The glider's path length for each of the transects surveyed, however, was considerably longer than that of the FV *Compass Challenger*, because of continuous small navigational adjustments required to keep it on track at the much slower speed. The current stratified random transect design used for the acoustic survey programme has transects that are mainly perpendicular to the coastline and, given the shelf topography, also the prevailing ocean current. Future integration of gliders into the survey design could consequently be restricted to their deployment in the nearshore to mid-shelf areas of both the West and South coasts. Alternative sampling designs that make use of the prevailing ocean current to maximise coverage of an area are likely to be more effective in situations where the gliders are employed in non-quantitative scenarios, such as fish scouting or fish migration studies.

The slow speed attained by the Wave Glider (typically 1.5 knots) is similar to the average swimming speed of small-pelagic fish schools measured off South Africa (Misund et al. 2003). Estimates of fish biomass are likely to be biased if fish are migrating within the survey area and the extent of the bias is likely to increase as the rate of fish migration increases relative to the rate that the survey progresses (Simmonds and MacLennan 2005). It is therefore conceivable that the glider could sample the same aggregations of fish on successive transects, particularly if transects are positioned perpendicular to the direction of migration and are surveyed in the same direction as that of the fish migration. This problem can be overcome by adjusting the length of transects relative to the transect spacing, thereby effectively increasing the speed of fish migration relative to the speed at which the survey progresses, or by ensuring that the direction of the survey is counter to that of the fish migration.

There remains a clear disadvantage to using only an AWG to survey stocks of small pelagic fish, particularly in upwelling and temperate shelf ecosystems, where several species of fish coexist. Whereas numerous attempts at remote species identification have been made (see review by Horne 2000) with various levels of success, most acoustic surveys still rely on trawl or net sampling of the acoustic targets to verify species composition and fish size, both being essential elements of density estimation by species. The further use and integration of AWGs or other unmanned platforms into survey programmes where various small pelagic fish of similar body shape, size and biology inhabit similar habitats, will rely on further development of remote species-identification methods, including for disaggregated, night-time mixed-species layers. In the interim, however, acoustic surveys could benefit from integrating AWGs into their survey designs, through cooperation with research vessels. Much of the survey time is typically devoted to covering vast areas of the ocean without detecting much fish. By allocating designated transects to AWGs, much of the research vessel's time could be devoted to sampling between AWGs in areas where fish have been detected.

Conclusions

The future of South African fisheries monitoring and assessment of associated ecosystem health faces significant challenges in the observational requirements required to meet scientific and management needs. This chiefly results from the large size of the ocean domain that has to be observed (>1.5 million km^2) and the cost in resources required to undertake this effectively. We introduce a new approach towards monitoring fish stocks and provide analysis of auxiliary environmental data that can be collected by gliders, such as wind strength and direction from on-board meteorological sensors and surface ocean currents from an ultrasonic water speed sensor. A robotics approach to this is novel and has not, to our knowledge, been successfully implemented, demonstrated and compared to collocated 'traditional' ship-based acoustics surveys, elsewhere in the world. Competing technologies to this are now decades old (i.e. using ships with acoustic sensors to measure the same parameters) and our approach provides numerous advantages towards enhancing this area of research and resource management through the novel integration of the required sensors onto autonomous platforms. The additional compelling benefits of this technology to acoustic sciences include being able to collect high-quality data extremely quietly, at high-resolution and continuously.

The ability of the AWG to conduct surveys remotely without the presence of humans allows it to be a low-cost alternative to ship-based surveys. Greene et al. (2014) present a fuller account of the potential financial and time savings achievable using fleets of WGs compared to survey ships within the United States fisheries context and region. The WG's ability to propel itself using freely available wave energy and to use solar PV panels to re-charge its batteries used to power sensors allows it to be at sea for extended periods. The potential to scale up to WG fleets will enable the space–time gaps inherent with ship-based surveys to be closed. This approach is competitive because expanded high-quality data collection can be undertaken at a considerably reduced cost compared with existing methods and technology, which renders year-round monitoring of the environment conceivable. Increased and continuous observational capability also enables scientists to monitor real-time responses of fish stocks to short-term environmental variability, which is of great value in understanding how climate change is likely to drive long-term changes in fish distribution and abundance. We envision new approaches to using fleets of both surface and profiling unmanned platforms to enable continuous monitoring of the ocean environment, with resulting larger volumes of temporally and spatially coherent data. This would facilitate unprecedented approaches to ecosystem management, strengthen ocean governance and support robust climate projections. This, in turn, would support the development objectives of South Africa, specifically those set out in national development initiatives, such as Operation Phakisa (www.operationphakisa.gov.za).

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