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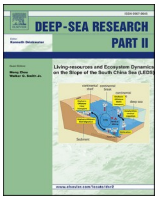

Ecological insights into abyssal bentho-pelagic fish at 4000 m depth using a multi-beam echosounder on a remotely operated vehicle

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ABSTRACT

Ecological and behavioral data on mobile, low density, benthopelagic animals is difficult to collect in the abyssal environment. However, these species occupy an important position in the abyssal food chain. At-depth ROV-mounted echosounder studies provide a powerful tool to gather *in-situ* information on abyssal benthopelagic assemblages and discern their distribution, behavior and habitat associations. This study presents a new perspective on mobile benthopelagic assemblages at the long-term study site, Station M (~4000 m), using a Seabat T20-S MBES mounted on the ROV *Doc Ricketts*. The targets (~45 m off the seafloor) are believed to be the abyssal grenadier of the species *Coryphaenoides armatus* or *C. yaquinae*, species known to dominate the mobile benthopelagic fauna at Station M. The swimming behavior of the targets indicated little evidence of avoidance or attraction to the slowly moving ROV and demonstrates the effectiveness of this platform to collect data on benthopelagic fish. The information on targets in close (<1 m) association with the seafloor from the MBES corresponded well to target densities recorded by the video transects. However, in addition the MBES resolved the distribution of targets up to 45 m above the seafloor. Target density had a small peak close to the seafloor (<1 m) but increased in density with height above the seafloor, exceeding the maximum near-bottom density by ~50 times. ROV-mounted MBES surveys can effectively provide data on the distribution and behavior of benthopelagic fish and further understanding of the pelagic-benthic links in the abyssal deep-sea.

1. Introduction

Predators and scavengers are a dominant group in the mobile benthopelagic fauna of the abyssal environment (Britton and Morton, 1994). Here they play a key role in deep-sea ecology through their impacts on prey populations and the consumption and dispersion of organic food falls at the seafloor (Yeh and Drazen, 2009; Drazen and Sutton, 2017). While this group plays an important role in the abyssal food-chain, information on their distribution and behavior is sparse principally due to the difficulties associated with data collection at abyssal depths.

Mobile benthopelagic animals have been studied in various global deep-sea regions, including the northeastern Atlantic (Martin and Christiansen, 1997; Gordon and Duncan, 1985), and the Mediterranean slope (Cartes et al., 2016). This group of animals have been the focus of studies at the long time-series study site in the abyssal northeastern Pacific (Station M), especially benthopelagic fish. Fish have been studied in detail using deep-sea imaging systems (Priede et al., 1994; Bailey et al., 2007), ingestible acoustic transponders (Priede et al., 1990) and *in-situ* respirometers (Smith, 1978). Imaging studies have included baited cameras (Wilson and Smith, 1984), towed camera sleds (Bailey et al., 2006) and long-term time-lapse camera deployments (Vardaro et al., 2007) (full details of sampling methods given in Priede et al., 2019). Together, these studies have provided information of the population structure, abundance, physiology and feeding ecology of mobile fish fauna in close association with the seafloor (Priede et al., 1994; Drazen and Sutton, 2017). The abyssal grenadier, *Coryphaenoides armatus* (Hector, 1875) and rough abyssal grenadier, *Coryphaenoides yaquinae* (Iwamoto and Stein, 1974) are two morphologically similar macrourids known from these studies to dominate the demersal fish biomass in the abyssal Pacific Ocean, including Station M (Jamieson et al., 2012). The species *Coryphaenoides leptolepis* (Günther, 1877) is less abundant than the other two *Coryphaenoides* species but has been observed in low numbers in the ROV dives at Station M (Priede et al., 2019). *Coryphaenoides* are mobile predators and scavengers on nekton, carrion and benthic infauna that are adapted to feeding in the food-limiting

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environment of the deep sea (Smith and Hessler, 1974, Smith, 1978; King and Priede, 2008; Priede et al., 2019). Here, their feeding activities play an important role in the transfer of energy across the abyssal seafloor and throughout deep-sea food webs (Haedrich and Henderson, 1974; Collins et al., 1998; Drazen and Sutton, 2017). Changes in the densities and activity of abyssal *Coryphaenoides* spp. at Station M, recorded from towed cameras or baited camera systems, have been correlated with changes in food source. Grenadier numbers increased following an elevation in the abundance of mobile epibenthic megafaunal prey (Bailey et al., 2006) and grenadier activity rose after an increase in the downward flux of particulate matter to the seafloor (Priede et al., 1994). Information on the density and distribution of abyssal grenadier, particularly in relation to changes in organic food supply, is an important component in understanding the deep-ocean food web and carbon-cycle processes.

In response to the need for density estimates of deep-sea fish populations, the relative abundance of abyssal fish fauna at Station M has been primarily assessed using baited underwater camera systems. This methodology involves modelling the process of the detection, attraction and arrival of grenadiers at the baited underwater camera system using an inverse square relationship (Priede et al., 1990, 1994). This method has proved successful in producing density estimates comparable to some trawl surveys (Armstrong et al., 1992; Priede and Merrett, 1996) but is restricted to sampling the area of influence of the emanating bait plume and to the scavenger species attracted. Echosounders however provide a means to monitor marine fauna within large volumes of water at a high spatial and temporal resolution (Benoit-Bird and Lawson, 2016). A number of factors do however restrict the use of typical vessel-mounted systems for the study of fish in water depths greater than 2000 m (Kloser, 1996; Priede and Merrett, 1998). These include a large acoustic shadow if the transducer is used over steep bottom topography and complications from beam thresholding (Foote et al., 1991), an uncertain sound absorption constant (Fisher and Simmons, 1977), and surface effects from bubbles (Løvik and Dalen, 1981) and ship motion (Stanton, 1982). For deep-sea acoustic applications, transducers have been mounted on underwater sampling vehicles and platforms (such as an autonomous split-beam acoustic array (Smith et al., 1989), a deep-towed transducer (Kloser, 1996) and an autonomous underwater vehicle (AUV) (Benoit-Bird et al., 2017) to overcome these limitations.

Multibeam echosounder (MBES) technology is commonly mounted on modern underwater sampling vehicles such as AUVs and remotely operated vehicles (ROVs) to map the deep-seafloor with high resolution over large spatial scales (Sen et al., 2016; Huvenne et al., 2018). MBES are also being increasingly applied to the quantitative estimate of fish densities due to the benefits of these systems to measure a larger volume of water than single-beam echosounders with a similar (or improved) resolution (Gerlotto et al., 2000; Melvin and Cochrane, 2015). In the deep-sea, MBES mounted on mobile sampling platforms such as AUV or ROV have the potential to provide valuable tools for the study of deep-sea pelagic and benthopelagic targets. An advantage is that the ROVs or AUVs can perform other operations, such as video camera transect surveys, simultaneously with the collection of target backscatter information by the MBES. For example, an AUV-mounted MBES was used to detect and quantify the movements of benthopelagic backscattering targets (likely to be individual fish or squid) at ~ 800 m in Monterey Bay (Dunlop et al., 2018). ROVs also represent a potentially effective platform for acoustic technology to detect and quantify deep-sea fish communities, especially at Station M where the ROV *Doc Ricketts* is annually deployed for benthic imaging surveys (Kuhnz et al., 2014). ROVs, however, have also been observed to cause an avoidance response in some deep-sea species, including the roundnose grenadiers (*Coryphaenoides rupestris*), which is thought to react to artificial illumination and vehicle noise (Trenkel et al., 2004).

The present study focuses on determining the depth-related trends in the distribution of mobile abyssal benthopelagic animals in the north-eastern Pacific using acoustic backscatter data collected from an MBES mounted on a terrain-following ROV. Here, we investigate the ability of the MBES-method to detect, characterize and provide quantitative data on the mobile benthopelagic fauna as part of the Station M long-term abyssal time-series. A key question in relation to the survey method is whether the presence of the ROV platform can influence faunal behavior.

2. Materials and methods

2.1. ROV-mounted multibeam echosounder equipment and survey details

A high-resolution MBES was mounted on the ROV *Doc Ricketts* to collect backscatter data at Station M (35° 10′N, 122° 59′W) at ~ 4000 m in the abyssal Northeast Pacific (Fig. 1). The ROV was deployed from the RV *Western Flyer* during the Pulse 67 Station M cruise on the 15 November 2016, and the MBES transect was recorded between 17:48 and 19:05 (UTC). A Reson 200/400 kHz Seabat T-20s (Teledyne RESON, Denmark) MBES was used to collect data at a frequency of ~200 kHz (512 beams over a 140° swath). The Seabat T-20s has a maximum range of 225 m and was not calibrated. Calibration of a MBES increases the utility of the instrument (Lanzoni and Weber, 2012). However, uncalibrated MBES can still provide useful information on target spatial characteristics and behavior (Brehmer et al., 2003; Kupilik and Petersen, 2014). The MBES transducer was mounted on the base of the ROV sled and was deployed facing downwards towards the seafloor. A Teledyne RDI 1200 kHz navigator doppler velocity log (DVL) and an ultra-short baseline (USBL) system (Sonardyne Ranger 2) collected positioning and altitude data during the transects. The ROV flew in a straight line on a mean bearing of 312.04° (±2.48°) to cover a transect of 1.95 km across the abyssal seafloor. During this transect the ROV maintained a speed of 0.15 ms^{-1} at a height of 50 m above the seafloor. Midwater video transects were collected simultaneously with MBES data using a high-definition video camera to validate the acoustic signal and to assist with the classification of detected targets. Benthic video-only transects were also recorded at Station M during other ROV dives in the Pulse 67 cruise between the 11th – 14th November 2016. During these benthic transects the ROV flew at an altitude of ~1 m above the seafloor and at a speed of 0.15 $m\,s^{-1}$ for a cumulative distance of 2.73 kms.

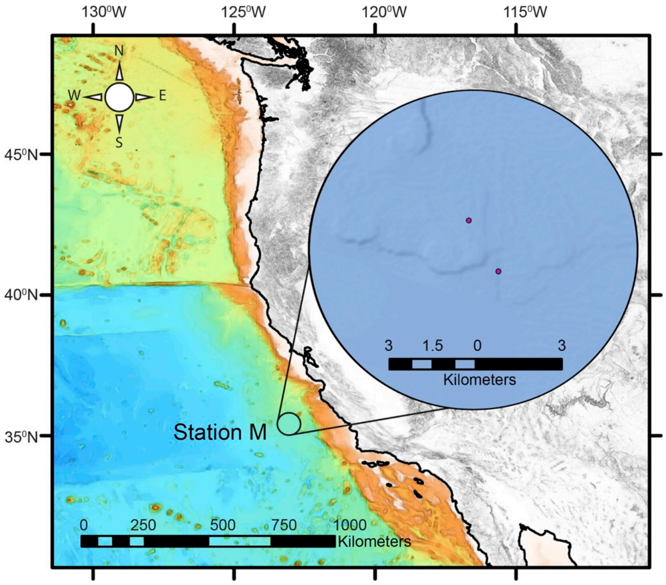

Fig. 1. Map of the survey location at Station with the transects start and end locations marked.

2.2. Acoustic data processing

The MBES backscatter data were processed using Echoview version 9.0 (Echoview Software, Australia) following an adaptation of the MBES processing steps outlined in Dunlop et al. (2018). During pre-processing, the echogram was visually inspected and the echosounder-detected-bottom corrected. Acoustic data contaminated by background noise from other deployed instruments and the ROV motor and noise were discarded using algorithms and settings to clean the data. The Echoview Kovesi imaging denoising algorithm (derived from Kovesi, 1999) was used to remove unwanted statistical noise from the pings. The Multibeam Background Removal algorithm further reduced unwanted noise, this time from reverberation, acoustical and electrical noise. Data directly below the ROV was largely contaminated by noise, therefore data within 5 m of the transducer was removed from the analysis.

The cleaned acoustic data were further processed using the Echoview® Multibeam target detection operator to extract single targets and calculate their *in-situ* relative target strength using a target strength frequency distribution between −100 and 20 dB. The Echoview® fish tracking algorithm finds and tracks single echoes over several pings. The algorithm was applied to extracted single targets to obtain identifications of the same target's movements in space and time as it crosses the beam over multiple pings. It was specified in the algorithm to detect at least 5 cross-target detections per track. Full details of the parameters using the Echoview® target strength analysis are found in Table 1.

Table 1
Echoview parameters for target strength analysis using single-target detections and fish tracking algorithms.

Processing Step	Key Operators	Settings
Cleaning	Ping Subset Operator	
	Kovesi Image Denoising Operator	Minimum wavelength = 4 Softness = l Standard deviation to reject = 4
	Multibeam Background Removal Operator	Minimum threshold = 20 Window size (pings) = 3 Algorithm = median Percentile = 60 Minimum SNR (dB) = 1.00
Detection and Tracking	Multibeam Target Detection Operator	Specified maximum range (m) = 50 Link target clusters = no Max. horiz/vcrt. Linking dist. (beams, samples) = 1.49/1.49 Min. candidate length/height (cm) = 0.001/0.001 Min. target length height (cm) = 0.001/0.001
	Target Conversion Operator	Filter targets = no
	Processed Data Operator	
	Target Property Threshold Operator	Threshold targets by = Target length across beams Minimum threshold (cm) = 0.01 Maximum threshold (cm) = 150
	Target-Tracking A1gorithm	Single target thickness source/ factor = Transmitted pulse length/ 0.01 Data = 4D (range, angles and time) Alpha (major axis/' minor axis/ range) = 0.4/0.4/0.4 Beta (major axis/minor axis/ range) = 0.4/0.4/0.4 Excl. disi, (m) (major axis/minor axis/ range) = 1/1/1 Missed ping expansion (%) (major axis/minor axis'range) = 25/25/25 Weights (major axis/minor axis/ range/TS/ping gap) = 1/1/1/0.5/5 Min. no. single targets/pings in track = 5/5 Max. gap between single targets (pings) = 5

2.3. Target characterization and classification

Tracked targets were characterized by their location and depth in the water column using the metrics target depth, track length, duration and tortuosity. Some groups of targets had characteristics that showed they were incorrectly connected as tracks. These unrealistic tracks were identified based on their total distance covered along with the number of targets and were removed from the analysis. Track characteristics used to assess the response of targets to the moving ROV platform included: (1) changes in track horizonal and vertical direction, (2) changes in track depth, (3) track tortuosity (measured as the distance covered by the track divided by the straight-line distance between the endpoints of the track, a measure of departure from a straight line, which has a value of (1) and (4) major-axis angle of the track (i.e. the angle of horizontal movement) were used to analyze data for the presence of avoidance behavior. Images and videos collected from the towed camera sled, ROV video-transect and baited underwater camera deployments previously collected at Station M have shown that deep-sea grenadiers of the genus *Coryphaenoides* dominated fish assemblages at Station M (Priede et al., 1994, 2019; Bailey et al., 2006; Kuhnz et al., 2019). Pelagic and benthic video-transects collected alongside the MBES data in this study were also used to help confirm target classification (Kuhnz et al., 2019). Benthic videos were annotated using the Monterey Bay Aquarium Research Institute (MBARI) Video Annotation and Reference System (VARS) (Schlining and Stout, 2006).

3. Results

The low speed of the ROV vehicle enabled 3475 long traces of individual targets crossing the beam over several pings to be tracked in the water column from the seafloor to 45 m altitude above the sea floor. (Fig. 2.). The number of target detections per track ranged from 5 (the threshold used to define tracks) to 160 (17.9 target detections ± 0.36 (mean ± SE)). Tracks covered between 0.1 and 23.7 m (1.8 m ± 0.07 (mean ± SE)) in space and targets were tracked between 1.1 and 49.2 s (5.2 s ± 0.10 (mean ± SE)). In general, there was a significant relationship between the density of tracks (individuals m^{-3}) and height above the seafloor (regression; $F_{1,}$ 43 = 290.1, r^2 (adj) = 0.871, p = 0.001) (Fig. 3). Track densities at 45 m altitude reached 0.5 individuals 1000 m^{-3} and declined to 0.006 individuals 1000 m^{-3} at 6 m water depth above the seafloor. However, a local peak in track density (0.01 individuals 1000 m^{-3}) was observed in close association with the seafloor.

The measure of tortuosity represents the divergence from movement in a straight line. Based on tortuosity, the majority of the tracks detected by the MBES moved in a straight line tortuosity ranged from 1 (a straight line) to 3.88 (mean 2.31 ± 0.03 (mean ± SE)). The ROV moved in a northwesterly direction while 82.2% of the tracks moved within a 90° angle in the same direction (i.e. 270–360°) as the ROV (Fig. 4a). The vertical movement of tracks in relation to the movement of the ROV was minimal. The mean (±SE) change in target depth was −0.01 m ± 0.10 and ranged between - 1.6 m (downwards) to + 1.3 m (upwards). No specific direction of vertical movement was favored by the targets in relation to the ROV. For example, 49% of tracks moved in a downwards direction, while 50.1% moved upwards (Fig. 4b).

Coryphaenoides armatus/yaquinae and *C. leptolepis* were the primary benthopelagic fish fauna observed in both the benthic and pelagic video transects recorded simultaneously at Station M. Twenty-nine individuals of the genus *Coryphaenoides* spp. were observed in the benthic transects in close association with the seafloor. This number corresponded to a density of 10.6 individuals per km^2 (equivalent to 0.0106 individuals 1000 m^{-3}) (data reported in Kuhnz et al., 2019). In addition to *Coryphaenoides* spp., larvaceans (class Appendicularia), siphonophores and copepods were also commonly observed in video transects in the water column.

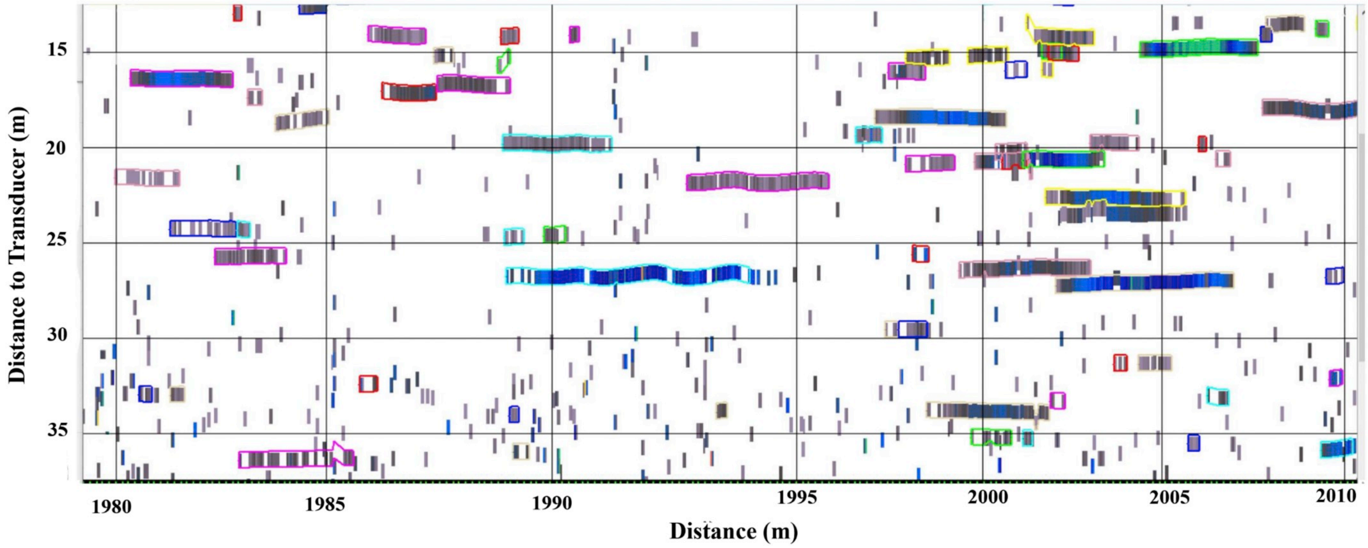

Fig. 2. An Echoview screenshot of the single target echogram in a 2D view with depth (meters) on the y-axis and transect distance (meters) on the x-axis.

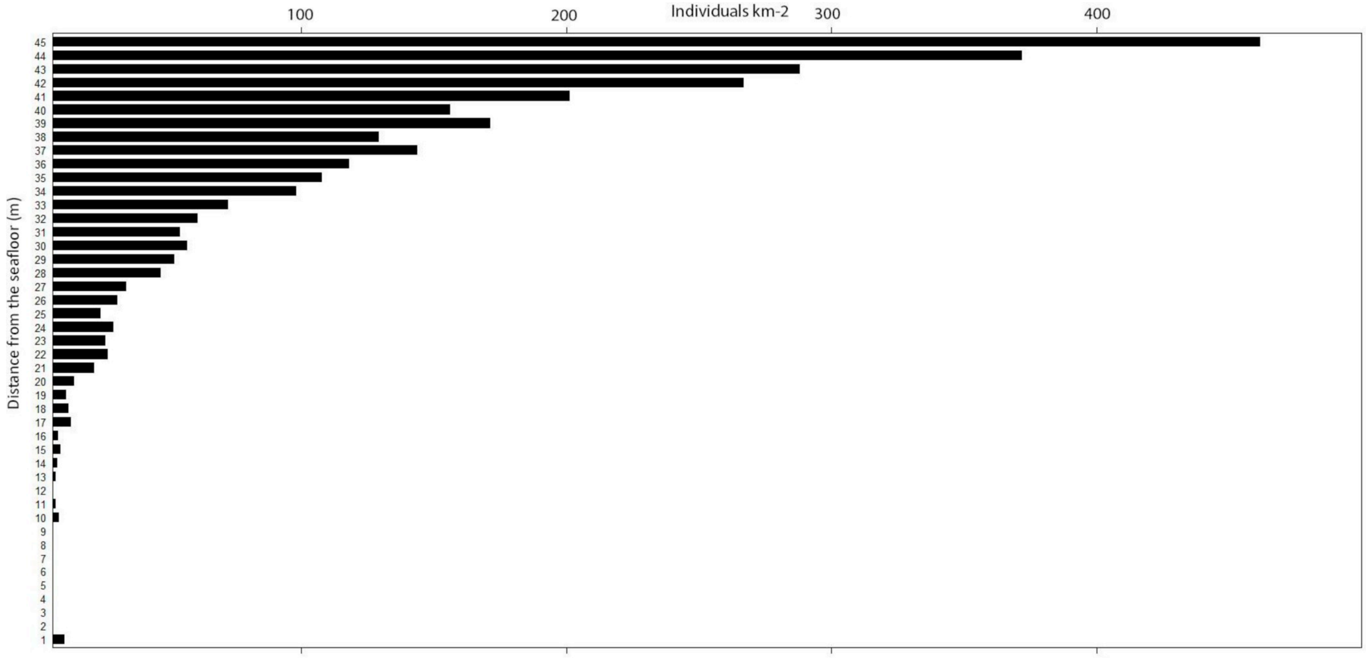

Fig. 3. Histogram of the distribution of target density with depth between the seafloor (0 m) to 45 m above the seafloor.

4. Discussion

The combined use of a ROV-mounted MBES and high definition video camera, has demonstrated a new perspective on studying the mobile benthopelagic fish at Station M. Benthopelagic targets, most likely deep-sea grenadiers of the genus *Coryphaenoides* that are known to dominate the benthopelagic fish fauna at Station M (Bailey et al., 2006; Priede et al., 2019), were tracked in the MBES data. The swimming behavior of the observed targets were relatively unaffected by the presence of the ROV *Doc Ricketts* and an increasing density of benthopelagic targets with distance from the seafloor was observed.

The behavior of some fish is unchanged by the presence of a ROV platform, however others can respond to the noise generated by the lights, motors, propulsion, bow wave, and hydraulic power (Krieger, 1992; Stoner et al., 2008). For example, a lighted ROV elicited a moderate response in roundnose grenadiers (*C. rupestris*) in the Bay of Biscay at a water depth between 1100 and 1500 m (Trenkel et al., 2004). However, it must be taken into account that *C. rupestris* has a more highly developed visual system than *C. armatus/yaquinae* (Wagner, 2001), making the species more susceptible to light from the ROV. In Monterey Bay, a clear avoidance response in benthopelagic fish at ~800 m was elicited by the seafloor mapping AUV *D. Allan B.* moving through the water and was resolved by a SeaBat 7125 “swath” MBES. These targets displayed a consistent avoidance movement downwards and away from the AUV (Dunlop et al., 2018). The reaction of fish to an ROV can depend upon the vehicle operating speed and also the propulsion system (Trenkel et al., 2004; Stoner et al., 2008). The AUV in Monterey Canyon was moving at 1 m s^{-1}, a speed 6.7 times faster than the ROV at Station M. However, the ROV *Doc Ricketts* was using lighting and hydraulic propulsion, both known to impact the behavior of deep-sea fauna (Lorance and Trenkel, 2006; Ryer et al., 2009). The behavior response of a target to a moving vehicle is also species

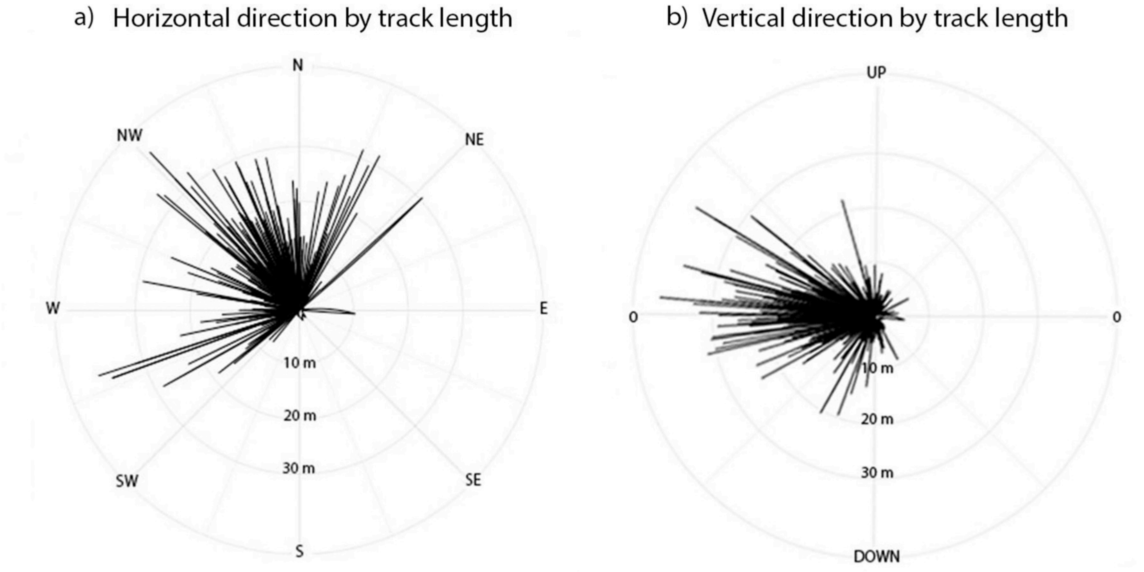

Fig. 4. Polar plots of the vertical and horizontal direction of tracked targets by distance.

dependent (Stoner et al., 2008). The fish fauna at 800 m in Monterey Canyon were dominated by the species (i.e. *C. acrolepsis*, *Antimora microlepsis*, *Alepocephalus tenebrosus*, *Dosidicus gigas*, *Lycodapus* sp and *Merluccius productus*), while the benthopelagic fish fauna at Station M by grenadiers (*Coryphaenoides* spp.) (Bailey et al., 2006; Drazen and Haedrich, 2012). The behavioral response of a species has been suggested to be dependent on the tradeoff between foraging and predator avoidance (Lorance and Trenkel, 2006). Grenadiers at Station M have no natural predators and therefore are less likely to display a strong avoidance response to the moving ROV. A study in the abyssal Northeast Atlantic found that *C. armatus* explored baited landers and suggested that the species lacked a hiding instinct (Jamieson et al., 2006). Acoustic tracking studies of abyssal grenadiers by Priede and Smith (1986) north of Hawaii at 5800 m water depth, found grenadier populations that were relatively immobile, patchily distributed and unaffected by sampling occurring elsewhere on the site. In addition, *C. armatus* observed in towed-camera surveys at Station M did not respond to the presence of the camera sled by either changing direction or orientation until the sled was very close (Bailey et al., 2006). It should however be noted that it is possible that fish could be avoiding the ROV outside the water volume observed by the downward orientated echosounder and go unobserved. Much of our understanding on the behavior of the abyssal grenadiers has been collected at Station M using baited underwater camera systems, ingestible acoustic transponders and towed and time-lapse cameras (Priede et al., 1986; Bagley anf Priede, 1997; Bailey et al., 2002; Vardaro et al., 2007; Priede et al., 2019). Ingestible transponders have allowed the behavior of two species of Grenadiers (*C. armatus* and *C. yaguinae*) swimming away from a bait sources to be observed (Priede et al., 1990; Armstrong et al., 1992). Wilson and Smith (1984) proposed that *Coryphaenoides* adopt a sit and wait strategy on the seafloor until the odor of a carcass is detected but further work has shown that grenadiers have a tendency to move across-current and swim independently of bottom currents to forage at a low continuous speed to reduce energy demands (Priede et al., 1990; Ruxton and Bailey, 2005). This swimming behavior is consistent with that observed here in the tracks of targets at Station M. The same camera systems have generated density estimates of benthopelagic fauna close to the seafloor (1 m above) at Station M. Densities are reported in individuals per km^2 or hectare^2 because of the small volume sampled. The volumetric density estimates from the MBES at 1 m above the seafloor study were integrated to areal densities, resulting in a mean value 10.5 individuals per km^2. This can be compared to 10.6 individuals per km^2 recorded in the ROV video camera transect surveys conducted in combination with the MBES surveys. This demonstrates that the densities of benthopelagic fish recorded by the ROV-mounted MBES are comparable to those recorded by the ROV-camera transects. The MBES system however, can also record fish densities at other depths throughout the water column providing a greater understanding of benthopelagic fish distribution and their role in the abyssal environment.

The benthopelagic layer creates an area of enriched pelagic biomass 10s–100s of meters above the seafloor (Smith, 1982). Here benthopelagic fish feed in the water column close to the seafloor where they play a role in both the lateral and vertical transport of organic material (Priede and Smith, 1986; Priede et al., 1990; Jamieson et al., 2006). The increasing density of targets with distance from the seafloor over the range studied here at Station M shows that many benthopelagic fish are active in the benthopelagic layer at least up to 45 m above the seafloor. Many detailed studies of deep-sea benthopelagic fish fauna have been made close to the seafloor or in the area directly above (Priede et al., 1994; Jones et al., 2003; Bailey et al., 2006). This dataset clearly illustrates the importance of also sampling higher into the water column to fully understand how abyssal benthic systems interact with the benthopelagic environment. Some studies have examined deep-sea pelagic biomass through the ocean layers and have shown this biomass to decline with water depth (Roe, 1988; Priede and Merrett, 1996; Priede and Froese, 2013). For example, Collins et al. (2005) reported a greater abundance of smaller *C. armatus* at shallower depths in the Northeast Atlantic, over a depth range of 800–4800 m.

This proof-of-concept study demonstrates that an ROV-mounted MBES survey can effectively provide ecologically valuable data on the distribution and behavior of benthopelagic fish at an abyssal site. However, further replication of these methods and the deployment of a calibrated MBES system would likely advance the findings of this study. The platform appeared to produce minimal observer bias from avoidance behavior in the taxa of interest at Station M and thus minimizes target orientation changes that can affect backscattering strength and target detection over background scattering. These data add new insight into benthopelagic fish behavior away from the seafloor. This is a valuable complement to furthering understanding of the pelagic-benthic links in the abyssal deep-sea.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dsr2.2019.104679.

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