Electronic Monitoring Performance in a Developing Deep-Set Fishery for Swordfish, *Xiphius gladius*, off California

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ABSTRACT—Electronic monitoring (EM) systems have been developed to facilitate fisheries data collection in many industrialized fleets but remain less common onboard smaller vessels. This work tested the performance of small-vessel EM systems to meet the reporting objectives in the California deep-set buoy gear (DSBG) fishery for swordfish, Xiphias gladius. *Two EM service providers were contracted to develop monitoring platforms, which included both 1- and 2-camera systems. Initial testing was performed onboard a research vessel to identify functional configurations and refine data collection procedures prior to commercial testing.*

Commercial trials were performed onboard four vessels during the 2020–21 fishing seasons, resulting in 126 electronically monitored set days. Fishery performance metrics from EM records were compared between service providers, fishing logbooks, and records from NOAA-certified observers. Catch comparisons yielded full agreement (100%) for both target (109/109) and incidental catch (9/9) between the 2-camera EM system and logbook records. The 1-camera system yielded 88% agreement (52/59) for target catch and 14% (1/7) for incidental catch. Unquantified catch events occurred outside the 1-camera field of view onboard larger vessels with independent hauling and catch-processing areas. Collectively, this study demonstrates that EM can be used to accurately document fishery catch statistics in the developing commercial DSBG fishery.

Introduction

Fishery monitoring and observation provide the basis for which accurate catch statistics can be generated, allowing managers to document and respond to fishery performance trends over time (Gilman et al., 2017; Bradley et al., 2019). Monitoring can provide critical fishery information such as estimates of effort, total catch and discards, protected species interactions, and issues related to fleet operations (Brooke, 2015; Wang and DiCosimo, 2019; Brown et al., 2021). Traditional forms of at-sea monitoring typically entail active fishery observation, which can be in the form of either human observers or electronic monitoring (EM) (Brooke, 2015; Moncrief-Cox et al., 2020). EM includes the use of different activity sensors and cameras positioned on vessels to remotely record fishing activity and catches (Gilman and Zimring, 2018; Carnes et al., 2019; van Helmond et al., 2019).

Given concerns over biases associated with self-reporting, human observers have long been considered the industry standard for ensuring the accuracy of fishery data collected at sea (Brooke, 2015; Curtis and Carretta, 2020). However, the high costs and logistical difficulties associated with staffing and supporting physical observers continues to offer challenges for fishing operations around the world (Haigh et al., 2002; Mangel et al., 2013; Alfaro-Córdova et al., 2017). Additionally, issues related to personal safety and liability as well as intimidation and bribery may collectively contribute to the difficulty associated with staffing fishery observers and collecting accurate information from open ocean fisheries (Brown et al., 2021; Belhabib and Le Billon, 2022).

To help increase coverage rates and mitigate some of the issues that are often associated with human observation, several forms of EM technology have been developed for meeting regulatory and compliance needs (Gilman and Zimring, 2018; reviewed by van Helmond et al., 2019). EM has now been trialed and implemented on over 1,000 vessels worldwide, with the majority of the innovation to date focused on larger vessels from industrialized fleets (Carnes et al., 2019; Itano et al., 2019; Brown et al., 2021). More recently, effort has been directed towards meeting the monitoring needs of smaller, artisanal operations which often go overlooked due to their low relative value compared to more industrialized operations (Bartholomew et al., 2018; van Helmond et al., 2019). This is critical considering that over half of the world's fish production comes from small-scale artisanal fleets, many of which continue to lack any form of monitoring (Bartholomew et al., 2018; Arthur et al., 2022).

Identifying uniform monitoring solutions in many small-scale fisheries can be difficult due to variability in fishery revenue potential, vessel sizes, and differences in observational or monitoring objectives. Fortunately, EM technology has progressed sufficiently such that monitoring platforms can be designed to address a wide range of fishery objectives as well as regulatory and compliance needs (reviewed by van Helmond et al., 2019).

Despite these advancements to date, building an effective EM platform still requires custom system tailoring to meet vessel specifications as well as the monitoring objectives of the fish-

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ery (i.e., catch limits, bycatch quantification, logbook verification; Bradley et al., 2019; Moncrief-Cox et al., 2020). Field testing and verification is also needed to demonstrate EM effectiveness and relative performance compared to human observers (Gilman et al., 2020). This is especially important if the fishery is new and its characteristics have not been previously documented.

California Deep-set Fishery

Research and testing under Exempted Fishing Permit (EFP) status has led to the recommendation[1] and recent authorization[2] of deep-set buoy gear (DSBG) and linked buoy gear (LBG) under the West Coast Fishery Management Plan for Highly Migratory Species (Sepulveda and Aalbers, 2018; Sepulveda et al., 2024). During this project period, the DSBG fishery was operating under exempted status through the Pacific Fisheries Management Council (PFMC).

The DSBG fishery is artisanal in nature, with vessels typically deploying between 10 and 30 hooks daily, targeting swordfish below the thermocline during the day. The fleet is composed of vessels that range in size from 8–20 m, with trip durations ranging from 1 to 10 days. Fishery performance to date suggests DSBG to be highly selective for swordfish (>90% target catch), with non-target catch commonly released alive (Sepulveda and Aalbers, 2018; Aalbers et al., 2021; Sepulveda et al., 2024).

During this work, fishery monitoring requirements were set by regional managers (i.e., PFMC, NOAA) and met with physical observers staffed and provided by the NMFS West Coast Observer Program[3]. Although the DSBG fishery has been characterized as being low-impact and artisanal in nature, swordfish operations (i.e. pelagic longline, drift gillnet) in the north Pacific have had a history of protected species interactions, a factor that continues to support the use of physical observers and at-sea monitoring efforts (Carretta et al., 2004; Urbisci et al., 2017).

Given the lack of published data on the use of EM in any buoy-based fishery, we performed a pilot study to assess EM performance compared to both human observation and fishing logbook data (Murua et al., 2020; Brown et al., 2021). The objective of this study was to evaluate the suitability and efficacy of small-vessel EM systems as well as identify the system requirements necessary to effectively monitor the developing DSBG fishery.

The DSBG fishery is well suited for EM given that 1) smaller deep-set vessels have reduced observer accommodations, 2) daily fishery revenues are often insufficient for supporting human observer costs, and 3) fishery participants have voiced interest in exploring non-human monitoring options to reduce the financial and space-sharing burden associated with carrying human observers. Because physical observation was mandated during exempted fishing trials and gear development efforts (Bonito et al., 2022), this work capitalized on the data collected by human observers and summarized by the NMFS West Coast Region. Considering that neither of the small-vessel EM platforms utilized in this study had previously undergone extensive field tesing, this work documented fishery performance metrics (i.e., fishing locations and times, catch and effort) from both 1-camera and 2-camera data collection systems mounted onboard DSBG vessels targeting swordfish off southern California.

Methods

Location and Study Design

All research and EFP sets were performed within a portion of the Southern California Bight extending from approximately Point Conception to the U.S.–Mexico border. Because the EM technology tested in this study had not been used in any commercial application off California, testing was carried out in two phases. Phase I was performed aboard a research vessel to develop and refine the EM systems, followed by Phase II testing aboard active DSBG vessels to evaluate system performance during commercial fishing activities.

Gear configurations used during the study included both DSBG and LBG, which use the same basic hauling platform and have been shown to result in similar catch composition (Sepulveda and Aalbers, 2018; Aalbers et al., 2021; Sepulveda et al., 2014, 2024). Phase I research sets were performed under a Scientific Collection Permit (SCP) issued through the California Department of Fish and Wildlife (Specific Use Permit ID S-183330009-19106-001) as well as a Federal Letter of Acknowledgment issued through NOAA's NMFS West Coast Region.

EM Service Provider Selection

Independent surveys with EM service providers were conducted to identify a suitable small-vessel system for the study. The principal factors considered were cost and suitability onboard small vessels, as the fishery is artisanal in nature and the vessels are relatively limited in size (8–20 m). Two EM service providers were chosen to participate in the study, Saltwater Inc. (SI) and Shellcatch Ltd. (SC)[4], both of which had a history of performance in the EM field and were willing to work with the team to tailor a platform for the California deep-set fishery. Both providers offered comparably priced small-vessel systems and incorporated

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[1] National Oceanic and Atmospheric Administration. 2019. Federal Register 50 CFR Part 300, 84(42):7,323–7,325. (Avail. at https://www.federalregister.gov/documents/2019/03/04/2019-03493/fisheries-off-west-coast-states-highly-migratory-fisheries-amendment-6-to-fishery-management-plan). Accessed 11 July 2023.

[2] National Oceanic and Atmospheric Administration. 2023. Federal Register 50 CFR Part 660, 88, (88): 29544-29545. (Avail. at https://www.federalregister.gov/documents/2023/05/08/2023-09748/fisheries-off-west-coast-states-highly-migratory-fisheries-amendment-6-to-the-fishery-management). Accessed 11 July 2023.

[3] National Marine Fisheries Service West Coast Region Observer Program (avail. at https://www.fisheries.noaa.gov/west-coast/fisheries-observers/west-coast-region-observer-program). Accessed 11 July 2023.

[4] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA

data review services using their own respective software packages.

Saltwater Inc. (SI)

Although previous EM systems have been developed by SI for use in other commercial fisheries (i.e., pot, trawl, longline; Buckelew et al., 2015), the small-vessel system used in this study had not been tested in any other commercial application. During Phase I trials, SI initially provided a 1-camera system that was replaced in June, 2021 with a dual-camera system using hardware adapted from a commercially-available vehicle dash camera[5]. The resulting SI small-vessel EM platform used a custom waterproof digital video recorder (DVR) that interfaced with a GPS receiver and two independent camera heads extending from the unit with cable lengths of 1.5 and 3.0 m.

For purposes of comparison, one camera was mounted directly adjacent to the SC platform, while the other was positioned to maximize coverage based on the unique vessel layout. The DVR was mounted in an accessible area and wired with constant 12-V power from the vessel battery bank. An additional lead was wired to the main engine ignition switch such that recording was triggered only when the ignition was engaged, in order to conserve memory and minimize review time. Video was recorded at a rate of 30 frames s^{-1} and a resolution of 1080 pixels from both cameras with a 120°x100° field of view (FOV). Data retrieval required the physical exchange of 256-GB micro SD cards. Data were subsequently processed using the SI import tool and analyzed using the SI open-source review software. Datasets were stored on local hard drives, which were sent via courier to the service provider for external review.

Shellcatch Ltd. (SC)

The SC system used a single, self-contained, watertight camera unit that was coupled with the SC Virtual Observer app. The system was designed for monitoring artisanal vessels and has been previously used in small-scale fisheries in Latin America (Bartholomew et al., 2018). The SC system featured a built-in GPS receiver and captured still images at a rate of 20 frames min^{-1} with a 62°x48° FOV and a resolution of 1280 x 720 pixels.

Recording was automatically initiated when the integrated geographic restriction feature (geo-fence) detected vessel movement beyond a programmed radius surrounding its home port. Camera positioning and recording status could be verified in real time through the Virtual Observer app accessed from a personal electronic device (i.e., phone or laptop). Image and GPS data were stored internally until a bulk wireless data transfer was performed.

To facilitate data transfer, SC camera units interfaced with a Virtual Observer uploader tool, which required a wired internet connection. Data upload procedures required vessel operators or crewmembers to remove camera units from their mounted position and link the system with the uploader unit. When the uploader detected a camera unit nearby, wireless data transfer was automatically initiated at a rate of 4 MB/s from the camera unit to the uploader, which then transferred the data to the SC cloud-based server. Camera and uploader status were monitored online through the SC dashboard portal to confirm data transfer prior to remounting on the vessel.

Research Trials (Phase I)

Phase I testing was conducted onboard the R/V *Malolo* (14 m) during the 2020–21 fishing season to evaluate camera functionality, recording resolution/frame rates (i.e., still frames vs. continuous video), on/off protocols (ignition triggered vs. geo-fence), as well as data acquisition and transfer procedures. Both EM platforms were mounted, side by side, to the aft rail of the RV *Malolo* control tower at a distance of 12 m above the back deck to provide a view of the entire working area. The Pfleger Institute of Environmental Research (PIER) vessel had a similar layout as the participating commercial vessels and used the same hauling platform when fishing with either DSBG or LBG. All catch was tagged and released during research trials, thus direct comparisons of catch data were not conducted between experimental phases because of differences in fish tagging and handling procedures. Research sets were reviewed by the PIER team using corresponding image review software. Research data and review materials collected during Phase I were subsequently used to train EM service provider analysts and to create a set of standardized review protocols. Findings from Phase 1 were also used to determine preferred camera configurations and recording protocols for subsequent commercial trials. Phase 1 trials were initiated with an SI 1-camera system that was replaced in June, 2021 with an SI 2-camera system, which was selected for use during Phase 2.

EFP Trials (Phase II)

Upon completion of the research trials, Phase II testing was conducted during the 2021 fishing season onboard four commercial fishing vessels participating in deep-set EFP trials. Prior to installation, the team met with all cooperative fishermen to coordinate setup, discuss confidentiality clauses, and train crew on camera functionality, field diagnostics, application features, and data handling protocols. Cooperative fisherman participation was largely supported by their collective interest in developing ways to reduce the financial and space-sharing burden associated with accommodating physical observers. Both systems were mounted and configured as instructed by service providers and positioned side by side within the tower of each participating vessel (Fig. 1). Because EFP vessels were approved to use either DSBG or LBG configurations, mounting positions were selected to encompass both gear deployment and haul-back stations in addition to where catch was processed. However, the distance between hauling and processing sta-

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[5] Innovv K2 MotoCam. (Avail. at: https://www.innovv.com/innovv-k2). Accessed 11 July 2023.

Figure 1.—Commercial swordfish vessel outfitted with two electronic monitoring (EM) platforms, including both a 1-camera system from Shellcatch Ltd (solid red circle) and a 2-camera system from Saltwater Inc (dashed red circle) during experimental deep-set fishing trials within the 2020–21 fishing seasons.

tions on the two larger vessels precluded capture of the entire working deck from a single camera angle.

Participating vessels ranged in size from 11.6 to 19.5 m, (mean=15.4 m), operated by a captain and 1–3 crewmembers. Vessel selection criteria were consistent with established EFP terms and conditions, which specified that vessel captains must: 1) maintain accurate logbook entries for every set, regardless of observer presence; 2) carry a NOAA-certified observer on any trip that is requested of them; 3) notify PIER prior to departure on any trip and maintain consistent communication through daily check-in reports; and 4) immediately report the catch or interaction with any protected species. Vessel operators were compensated for the added undertaking of carrying both physical observers and housing EM systems as well as coordinating with team members for installations and data transfer. During Phase II trials, all swordfish caught were retained by the vessel for commercial sale and all incidental catch was released.

Observer and Logbook Records

Fishery observer training and data management was facilitated through the NMFS West Coast Region (WCR) Observer Program, while observer employment and placement onboard EFP vessels was coordinated through the contracted agency Frank Orth and Associates (FOA; Long Beach, CA). EFP vessel operators were required to contact the FOA observer coordinator 48 h prior to trip departure for determination of whether a physical observer would be placed onboard the pending trip. Because of altered staffing protocols due to COVID-19 restrictions, physical observers were not consistently available during the EFP trials.

Following trip debriefing, physical observer data were delivered to the WCR office for entry into an HMS database. Observer data records for all 2021 trips aboard EFP vessels that carried EM systems were requested by PIER for subsequent comparisons with output files from EM review and fishing logbook data. As described by Sepulveda et al. (2024), fishing logbook records were compared with daily check-in reports, state landing receipts, and observer data when available. Any discrepancies were identified for further evaluation.

Review Protocols

Prior to initiation of Phase II commercial trials, review training sessions were conducted with both service providers using the Phase I research trial data. Reviewers were given an overview of the gear types, configurations, and common species encountered in the fishery. Specific signatures, such as rapid changes in vessel speed or direction, were identified to help expedite the review process and better pinpoint significant events. The research team then worked directly with image analysts to develop consistent review protocols designed to capture the same information recorded by physical observers.

Recorded information included: 1) departure and arrival dates and locations; 2) number of days fished; 3) gear types deployed; 4) quantity of gear set; 5) catch composition; 6) catch condition and disposition; and 7) system performance issues. Event annotations were formatted with the intent to generate output files that were comparable with physical observer data, allowing for compatibility with existing NMFS databases. Because each system used a different review platform, the features of each are outlined individually below.

SI Review Platform Features

The SI system used the open-source O2 Review software package. The software utilized video data that was stored locally, either on a PC or external hard drive. Raw camera data underwent an upload process using the SI import tool, which formatted video files to be recognized by the review software. The user interface displayed video playback, a digital chart containing GPS coordinates and track lines, and a timeline displaying vessel speed. Information was displayed in separate windows to allow analysts to review multiple angles of video footage along with concurrent vessel speed and movements (Fig. 2A). The video playback rate was adjustable between 0.25 and 128x actual speed, allowing reviewers versatility in scrutinizing capture events and bypassing periods of inactivity. Annotations were made on the O2 review timeline and included fishing information as either point (i.e., observed swordfish capture event) or duration (i.e., linked buoy gear set) events, and trip information such as departure and arrival date and location. Any annotations made during the review process were saved in an associated data folder that could be viewed or modified on other devices.

SC Review Platform Features

The SC system used an online review portal (Shellcatch Review Dashboard), that accessed cloud-based image data that was stored on an SC server. The review interface displayed images, vessel speed, and GPS data on a single webpage that could be viewed at rates from 0.5 to 4x actual speed (Fig. 2B). Specific events (i.e., gear deployment, target species catch, bycatch) were annotated within designated fields adjacent to the timeline, such that exported data was properly categorized and associated with a specific time and location. All annotations were saved to the online dashboard for subsequent access by other reviewers.

Data Analysis

PIER analysts independently reviewed all Phase I research sets in addition to validating both SI and SC review data against fishing logbooks and observer records during Phase II trials. Daily catch and effort statistics from logbook and observer reports were compared to image review output data for all vessels and dates with EM records. Any differences between daily catch records were individually assessed to determine the probable cause of discrepancies.

Catch discrepancies were attributed to either a reviewer, camera, or logbook entry error. Loss of data caused by human oversight resulted primarily from poorly repositioning cameras after servicing, improper wiring, failure to download cameras on schedule, and damaging memory cards. Data loss attributed to human oversight contributed to discrepancies in the number of entire sets recorded by each monitoring system. The level of physical observation was also compromised during two trips that human observers became sea sick or needed to return to port, as well as on trips when observers were not available or logistical constraints prevented placement.

EM performance metrics used to evaluate specific features of each system included: 1) number of cameras, 2) type of imagery (still vs. video), 3) mode of data storage and transfer (cloud-based vs. data storage cards), 4) initiation triggers, and 5) review software package. Overall storage capacity was determined as the number of continuous recording days available for both EM systems. The level of fishing effort was estimated from the number of individual buoys or linked sections deployed along with the soak duration for each DSBG or LBG set. Calculations of hook-soak hours were based on the number of hooks deployed per buoy line or linked section and the daily fishing duration. The time required to review each set was documented for a subset of trips to estimate average daily review times.

Results

Phase I

All experimental sets aboard the PIER research vessel were made between Santa Cruz Island and the U.S.–Mexico border and out 60 km from the southern California coastline. During Phase I, a total of 23 research sets were conducted between 3 September 2020 and 8 June 2021 with EM systems onboard. The SC 1-camera system monitored all 23 sets, while the initial SI 1-camera system monitored 5 sets during Phase 1 prior to transitioning to the SI 2-camera platform. Image review outputs matched actual catch values for 100% of the target catch events on

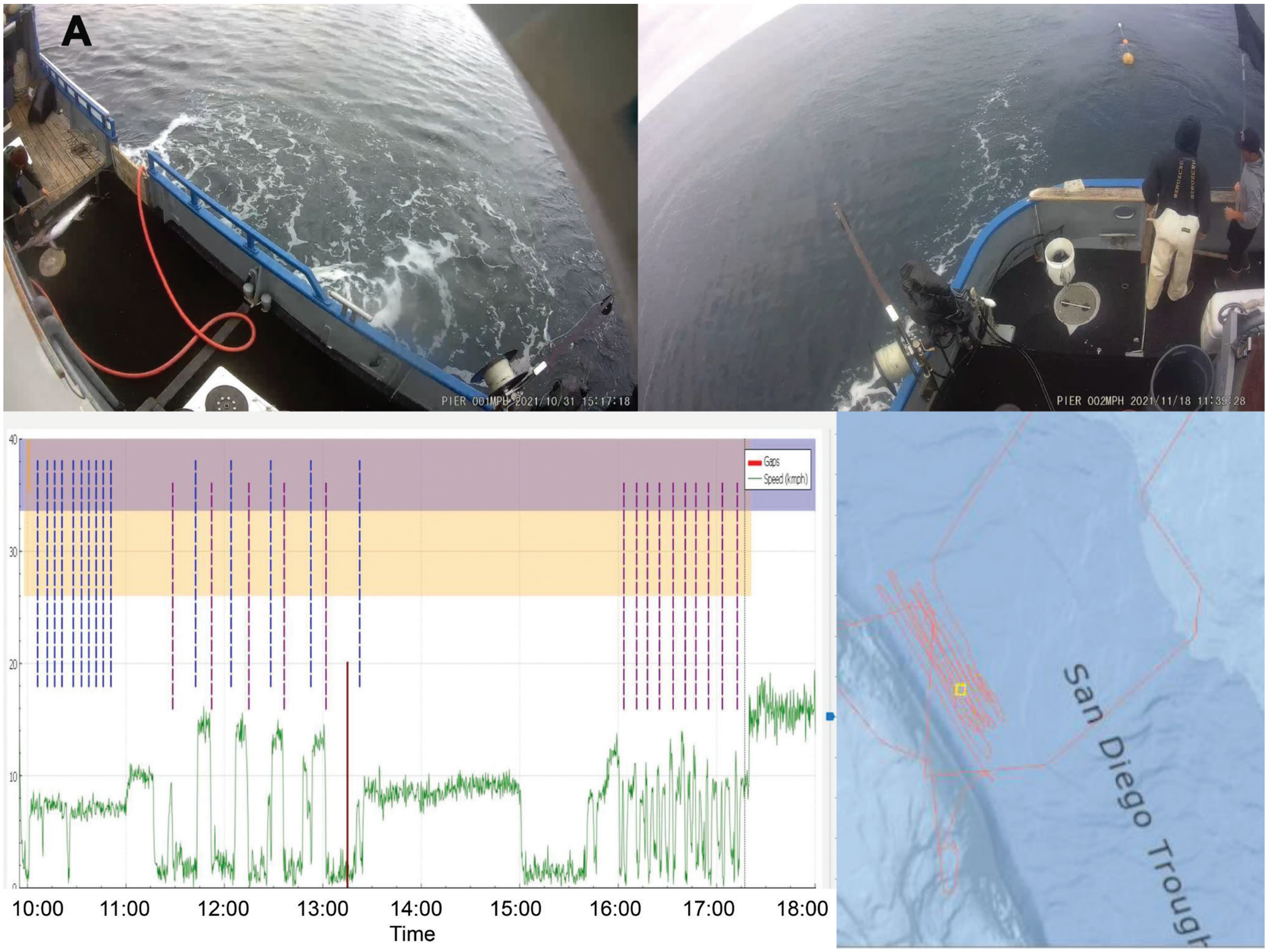


Figure 2.—Screenshot of the open-source O2 Review software package by Saltwater Inc. (A) and the electronic monitoring review software developed through the Shellcatch Review Dashboard (B), both featuring expandable windows for viewing overhead camera view of the working deck, as well as the image timeline, vessel trackline, and speed.

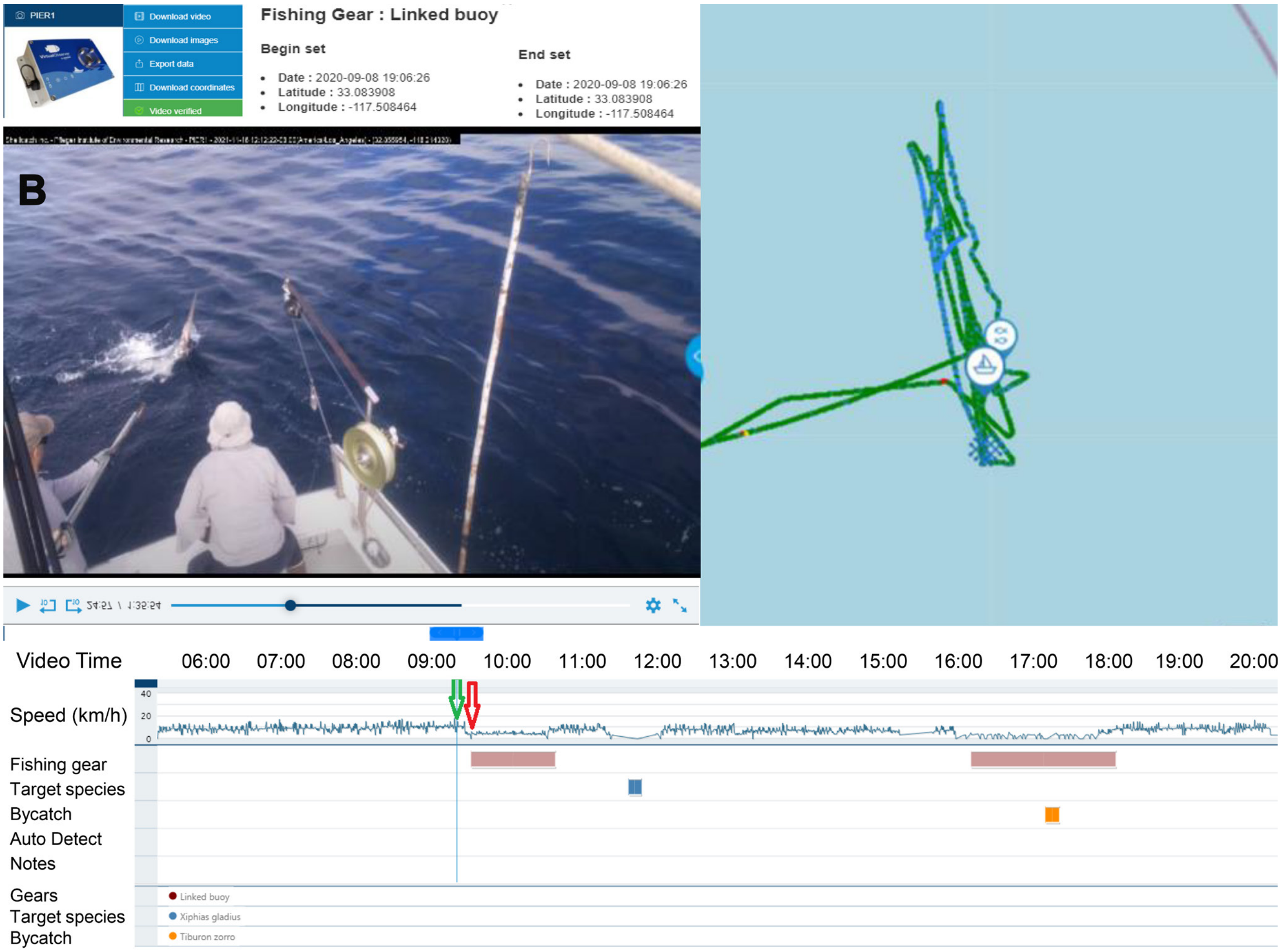
both the SC 1-camera (20/20) and the initial SI 1-camera (6/6) systems.

During the same sets, there were 10 total non-target interactions consisting of three different species, including the shark bigeye thresher, *Alopias superciliosus*; pelagic stingray, *Pteroplatytrygon violacea*; and blue shark, *Prionace glauca*. The SC system was operational during all 10 of the non-target capture events and EM records matched actual catch values for 70% (7/10) of the events. The SI system was operational during 9 of the non-target interactions and EM records matched actual catch values for 89% (8/9) of the events. Inability to identify catch was attributed to either subsurface release or catch being released outside of camera FOV.

Phase II

From 10 July through 3 December 2021, four participating vessels conducted 33 deep-set fishing trips, ranging in duration from 1 to 8 days (mean=4.2 d). A total of 126 sets were successfully recorded by either one or both of the EM systems, while physical observers documented 23% of the sets (29/126; Table 1). EM and observer records yielded good agreement (99% agreement, 139/140 events) with logbook data for both target and incidental catch. Observer records, logbook data, and image analysis confirmed the catch of just three species, swordfish (Fig. 3 A–C), bigeye thresher (Fig. 3D), and oilfish, *Ruvettus pretiosus*. The results of Phase II trials are presented individually below based on the presence of either 1 (SC) or 2 (SI) cameras.

The SC 1-camera platform successfully recorded 78 set days during Phase II trials. EM data showed agreement with logbook records for 88% (52/59) of the total swordfish catch. Of the 29 days in which a physical observer was



Fishing Gear : Linked buoy

Begin set

- Date : 2020-09-08 19:06:26
- Latitude : 33.083908
- Longitude : -117.508464

End set

- Date : 2020-09-08 19:06:26
- Latitude : 33.083908
- Longitude : -117.508464

Figure 2.—*Continued.*

also present, observer records verified that the SC 1-camera system identified 21/28 target catch events (75%). All 7 of the swordfish not documented by EM were caught aboard larger vessels with processing areas outside of the camera FOV.

For the incidental catch, EM data yielded agreement with logbook records for 14% (1/7) of the total non-swordfish catch. Five of these events were verified by the presence of a physical observer and two were based on fishing logbook records and verified by the other camera system. The incidental catch events not documented by the SC 1-camera system occurred outside of the camera FOV.

The SI 2-camera system successfully captured 97 set days during Phase II trials. EM data showed agreement with logbook records for 100% (109/109) of the total swordfish catch. Of the 22 days in which a physical observer was also present, observer records verified 15 of the target catch events. For incidental catch, the SI 2-camera system also yielded agreement with logbook records for 100% (9/9) of the total non-target events, with three of these events verified by the presence of a physical observer. One of the bigeye thresher catch events that was documented by both the EM system and physical observer was not present in the logbook (i.e., human or logbook entry error).

Table 1.—Reported catch numbers and verification levels documented by physical observers, cooperative fishermen, and two electronic monitoring (EM) systems employed during field trials onboard four commercial deep-set fishing vessels targeting swordfish off California.

Observation mode	# non-target events recorded vs. actual	% non-target verification level	# target events recorded vs. actual	% target verification level	Overall performance level
Human observer	5/5	100.0%	26/26	100.0%	100.0%
Fishing logbook	10/11	90.9%	129/129	100.0%	99.3%
1-camera EM	1/7	14.3%	52/59	88.1%	80.3%
2-camera EM	9/9	100.0%	109/109	100.0%	100.0%

Figure 3.—Captured images from electronic monitoring equipment outfitted on each of the four commercial deep-set buoy gear EFP fishing vessels used in this study to monitor target catch rates of *Xiphias gladius* (A, B, C) and non-target interactions prior to release, including *Alopias superciliosus* (D), which is identifiable by the elongated upper lobe of the caudal fin visible above the surface of the water.

EM System Performance

The average review time for each set day was ~60 min for the SC platform and ~30 min using the SI platform. On average, the SC system was able to record ~16.9 d of continuous video footage before bulk data uploads were required, and the SI system was able to record ~15.5 d of continuous video footage before SD card data transfers were needed.

Data retrieval and download varied between service providers and required the physical manipulation of either the SD card or camera unit. Secondary review was used to verify discrepancies between data sources for both target and incidental catch for both service providers. The SC system required secondary review for ~40% of the catch events (target and non-target) while the SI system required clarification for ~10% of the events.

Discussion

This study documented the performance of EM technology in monitoring catch, bycatch, and effort in a developing west coast fishery targeting swordfish. The study used two independent EM service providers and compared findings from small boat EM systems that were based on either a 1- or 2-camera platform. Comparisons of EM records with observer and fishing logbook records show that as long as the camera FOV adequately covered both the hauling and fish processing areas, the system was able to document 100% of the catch events.

For the SC 1-camera system, larger vessels with split working areas proved to be difficult to monitor with 100% confidence. Data from the initial research testing suggested that future handling protocols (i.e., bringing catch to the surface prior to release) may be useful for identification of non-target catch, regardless of the number of cameras used. Although this study showed that EM can accurately quantify fishing activity and catch composition in the developing deep-set fishery for swordfish, we suggest additional refinements that may help improve performance for any future commercial application.

EM-System Performance

This study simultaneously tested two comparably priced EM systems that differed in terms of their number of cameras, mode of data retrieval, and review software. Both platforms were initially tested onboard the R/V *Malolo* to assess system performance and allowed both service providers to address concerns or make adjustments prior to commercial testing. Based on findings from research trials, SI transitioned from its original 1-camera system to a 2-camera platform, which increased camera FOV and overall performance during Phase II trials.

Despite differences in system attributes, the primary factor that impacted monitoring efficacy was camera FOV. Previous studies also considered camera FOV to be a limiting factor in EM performance and similarly found that an individual camera view may be obstructed from portions of the working deck (Ames et al., 2005; Ames et al., 2007; Bartholomew et al., 2018). Because swordfish were often hauled onboard and processed in a different location from where non-target species were released, catch events may go undetected when the camera FOV did not cover both the hauling station as well as the deck door where catch was brought onboard. The SI 2-camera system used in this study had a collectively wider FOV and was more effective at capturing both the hauling and processing areas aboard larger vessels. Although the reduced FOV of the 1-camera systems resulted in a decreased number of documented catch events on the larger vessels (>17 m), the single camera was adequate for monitoring smaller platforms.

EM review accuracy (i.e., actual vs. observed interactions) and the amount of time required for review both improved from features of the SI 2-camera system (i.e., continuous video, the use of a wider FOV, and second camera angle). Analysts reported that reviewing continuous video, higher-resolution images, a wider range of playback rates, and multiple camera angles were advantageous over reviewing lower-resolution images with a reduced frame rate from a single-camera angle. However, based on the records from the smaller vessels, it was apparent that the fishing activities can be monitored successfully using still frames (20 fpm), as long as the FOV covered the entire working deck.

The different forms of data storage and transfer between systems each had benefits as well as disadvantages. While cloud-based platforms did not require physical data storage, difficulties associated with removing the SC camera between trips for data transfer resulted in poor re-positioning and missed data collection opportunities in this study. The retrieval of cloud-based data for review also involved loading and buffering, which added to total review times. The use of physical data-storage cards allowed data transfer without removing systems from their mounts; however, managing the transfer of cards between trips was also problematic and resulted in recording gaps and data loss. For example, a micro-SD card was broken during transfer resulting in the loss of data from 11 sets, a problem that could be minimized with reduced data handling.

Designing monitoring systems that incorporate backup mechanisms and minimize handling may considerably enhance data collection potential through reducing human oversight. Data stored locally on physical hard drives resulted in more efficient image playback and expedited review times. For both systems, limited storage capacity (~16-d recording time) was also problematic given that opportunities to transfer data between trips were not always convenient or possible, particularly when swordfish catch rates were high.

For example, fishing vessels rarely remained in port for more than 24 h when fishing was good and were commonly offloaded at odd hours, which impacted opportunities for data transfer between trips and led to data loss from human oversight during periods when catch rates were heightened. Although the 2 small-vessel EM systems used different start and stop mechanisms, both the geo-fence (SC) and ignition trigger (SI) were effective at reducing the overall amount of data recorded during periods of inactivity, which expedited review and extended system storage capacity.

EM Review Comparisons

Although not a principal goal of this study, a general comparison of the two service provider data review platforms was conducted to identify features that may be advantageous in a future fishery application. For both EM packages, image analysts used specific patterns found in the GPS tracks and vessel speed to identify capture events and reduce review times. Capture events were typically associated with a prolonged period of reduced vessel speed and changes in heading, whereas periods of transit or gear monitoring were more linear and at a consistent vessel speed (Fig. 4). Findings suggest that the development of machine learning algorithms may be incorporated into future review efforts, a strategy that may substantially reduce the time and costs associated with data review (Carnes et al., 2019; Qiao et al., 2020; Kay and Merrifield, 2021).

Review processes may also be streamlined by additional features used to detect fishing activity, such as optical sensors for spool or deck movement (Gilman et al., 2019). Review analysts noted that having a greater range of playback speeds (0.1–128x) and window sizes also expedited review times and often minimized the need for secondary analyses. Review times were also delayed due to limitations associated with remotely accessing data that was stored on a cloud-based server, an issue that may be overcome with access to data from local hard drives.

System Improvement Recommendations

Although this work has demonstrated the capacity of EM to successfully record and document deep-set fishing activity, we identified several areas in which a future system could be improved. A source of error in this study resulted from the frequent manipulation of both camera systems during data retrieval and transfer procedures. Given the difficulties and time associated with data transfer in addition to the loss of data caused by human oversight, an optimized commercial system

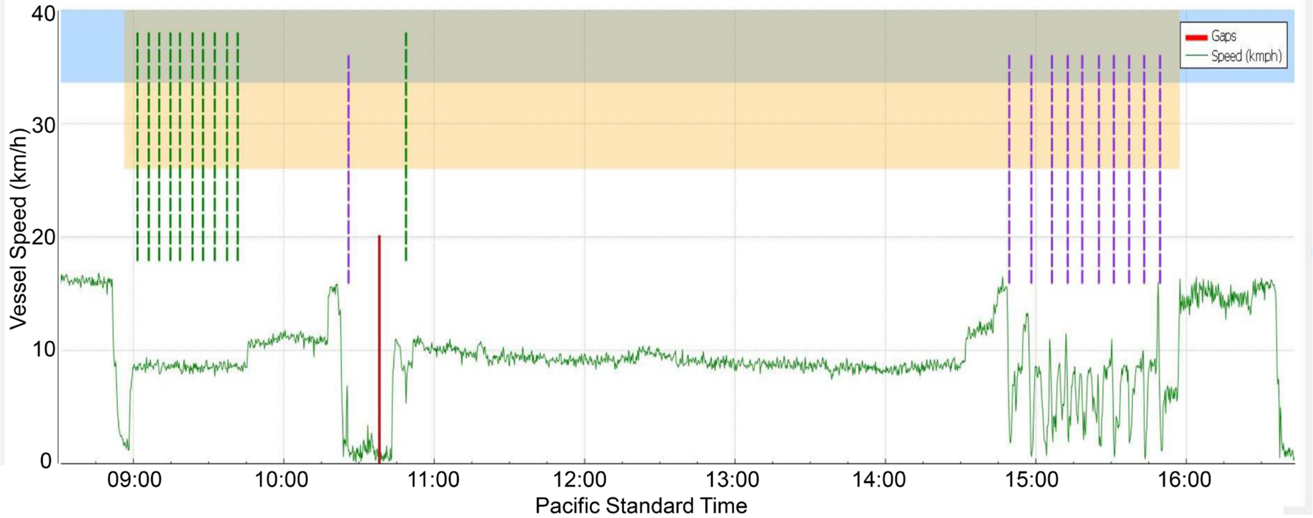


Figure 4.—Expanded timeline illustrating identifiable changes in vessel speed for an annotated catch event (red vertical line) that was used by image analysts to expedite review of EM footage using open-source O2 Review software package developed by Saltwater Inc. Green vertical lines represented gear deployment and purple lines represent gear retrieval events, while red shaded area represents duration of fishing effort.

should enable increased storage capacity to minimize camera handling and data transfer to the extent possible. Another option may be to integrate satellite-based data uploading capabilities for the remote transfer of data to a cloud-based storage network. Although satellite-based data transfer onboard small-vessels has previously been cost prohibitive, many west coast commercial vessels have recently identified more affordable at-sea connectivity options. Both initiation triggers used in this study prolonged periods between data transfers; however, future systems may benefit from a combination of features to help reduce the amount of nonessential activity recorded.

To account for FOV limitations, we would recommend the use of a 2-camera system on larger vessels, especially those with separate hauling and fish processing areas. Although efforts were made to minimize obstructions by mounting cameras in elevated positions, a 2-camera system provided a more unobstructed view of the entire working area onboard larger vessels. Increased FOV from more than one camera angle improved the proper identification of non-retained catch. However, to further enhance species identification, we recommend that all non-retained catch be held at the surface of the water prior to release. Modified handling protocols may increase EM identification accuracy by preventing the underwater cut off of branch lines (Emery et al., 2018; Carnes et al., 2019), a change that could also benefit physical observers that similarly may not be able to identify underwater or distantly released catch. The use of overhead or underwater illumination may also be useful to better identify catch released under low-light conditions.

DSBG Fishery Future Use of EM

Although the deep-set fishery has demonstrated a high level of selectivity for swordfish, the new fishery operates within the same areas that previously generated concern over protected species interactions (Carretta et al., 2004; Martin et al., 2015; Sepulveda and Aalbers, 2018). Considering the strong environmental standards among state and federal agencies, it is likely that an authorized west coast fishery will require some level of observation. Findings presented both here and in previous studies (Ames et al., 2007; Kindt-Larsen et al., 2012; Bartholomew et al., 2018) show that EM systems provide a reliable option for collecting catch information from vessels that may not be suitable for human observation due to a variety of reasons (i.e., size, safety, distance from port).

Considering the logistical challenges associated with physical observation onboard small-vessels (i.e., space limitations, insufficient bunk accommodations, and increased galley expenditures), it is evident that EM can benefit and compliment current fishery observation programs. Additionally, the use of EM can significantly reduce the overall cost of observation. Because the growing DSBG fleet is comprised of a wide range of vessel types and sizes, some of which are not suitable for accommodating physical observers overnight, the incorporation of EM as a future observation option may help provide an equitable observation platform for the developing west coast fishery or during other proposed EFP activities using different gear configurations. Lastly, given increased hesitancy to share personal space since the Covid-19 pandemic, EM may be more readily embraced and preferred by fishermen in the future (Erasmus et al., 2022).

Other Small-Scale Fisheries Future Use of EM

As EM technology improves and becomes more cost effective, the challenges associated with monitoring artisanal fishing operations are lessened. This study demonstrated the successful deployment and testing of two EM systems on small-scale commercial vessels (<12 m) and suggests that comparable designs could be used to effectively monitor fleets of even smaller boats. Considering that artisanal fisheries comprise a significant portion of the global bycatch concerns and total commercial harvest levels, the opportunity to document small-scale fishing activities may provide managers with the tools needed to better understand the vast numbers of unmonitored vessels that operate around the world.

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