***Study Objectives***

The objective of this study was to tag individuals of the species P. filamentosus with acoustic tags and track their movements relative to a BRFA to test the following hypotheses:

H1. Movement homerange by *P. filamentosus* exceed the scale of individual fishery closed areas (BRFAs).

H2. *P. filamentosus* make regular movements across BRFA boundaries.

H3. *P. filamentosus* do not utilize habitat uniformly.

***Study Area***

Initially the study area spanned both the island of Oahu and Penguin Banks, a broad flat shelf south west of the island of Molokai. Essential bottomfish habitat includes the contour band between 0-400 m depth with adult habitat primarily between 100 and 400 m. Fishery resources within this area are frequently targeted by commercial and recreational fishers.

Fishing activites are prohibited within the boundaries of three regional BRFAs. Oahu is separated from Penguin Banks by the Kaiwi channel spanning nearly 12 km at it’s narrowest point and extending to a depth of 700 m.

Following preliminary results which indicated that the study area far exceeded the size of the study area, the Makapuu region was selected as the primary study site for this project. This area, located off the Oahu’s windward side, extends outward from the south east tip of Makapuu point north off of the Lanikai peninsula. The site was selected because it contains both protected and non-protected habitat with sufficient area to capture the scale of bottomfish movements observed on the multi-island array, is important to the fishery, and is proximitate to a number of frequently used ports. A flat broad shelf protrudes east from the southern edge before terminating in deep slope to join the western side of the Kaiwi channel. To the north the shelf narrows to the north joining with a series of deeper shelves to form a number of submarine canyons empting to the to the island’s floor.

***Receiver Array***

***Network Design***

Deepwater acoustic tracking is relatively novel and presents a number of unique challenges compared to similar shallow water studies. Early efforts to tag and track *P. filamentosus* were limited by the scale and scope of the fixed receiver tracking array. During this study, a considerable amount of array hardware was deployed to operational depths exceeding those accessible by scuba, requiring deployment and recovery of receiver stations from a suitably sized vessel with the using of acoustic release mechanisms (Sonardyne, Vemco).

The array used to track tagged fish was made up of a number of fixed receiver stations strategically positioned throughout the study area. Each station consisted of an acoustic receiver and acoustic release was buoyed by three or four 10” deeprated trawl floats and moored by 180 pounds of concrete blocks with an acoustic release. Initial designs had receivers 20 m above the seafloor on exposed line. To minimize station loss from entanglement, later revisions placed receivers 6.1 m above the seafloor enclosed in a 1.5 inch diameter PVC tube.

During the 5 years of the project, the receiver array underwent an iterative design process incorporating insights from collected data and accomidating fluctuations in equipment inventory. An initial sparse (fisheries format) array monitored regions around Oahu and Penguin Banks. Sparse arrays use receivers placed with non-overlapping detection envelopes to monitor the residence and movement of tagged animals when over a broad area (Heupel, Semmens, and Hobday, 2006). The array piggybacked on an existing array for tracking deep water sharks and was constructed largely ad-hoc. Observations recorded with this configuration indicated that the network was of an inappropriate scale to monitor most movements of tagged opakapaka.

In December of 2014, a redesigned array focusing on Oahu and the Makapuu area in particular, was deployed. This array was a hybrid design consisting of both sparse and fence gate subarray components. Fence arrays, where receivers are placed in linear configurations such that their detection envelopes overlap, maintaining some acceptable threshold limit for detection while monitoring the movement of tagged individuals into or out of an area. Shortly thereafter, all remaining receivers were relocated to the Makapuu area and the fence subarray monitoring the BRFA’s southern boundary was repositioned and expanded closer to that boundary to more accurately detect individuals entering unprotected waters. Additional receivers purchased during the project’s third year were used to increase monitoring capacity in the north of the BRFA. Prior to the project’s fifth year, an additional 20 receivers were added to the network. These receivers were used in fence formats, monitoring areas directly inside the northern and southern BRFA boundary, while additional receivers reinforced sparse coverage within the BRFA, positioned along depth contours preferred by opakapaka.

Following the shift to Makapuu, positions of sparse sub-array components were determined in iterative stages using the Acoustic Web App telemetry optimization algorthm (Pedersen et al. 2013). Initially the sparse sub-array was designed to monitor deep 7 bottomfish habitat within the BRFA. Afformentioned ehnancement of the sparse sub-array during year 3 used the acoustic web app to improve receiver coverage in the northern half of the BRFA. Positions of 6 of the 10 receivers used to supplement the sparse array during year five were selected to monitor depths between 100 and 150 m, the preferred depth range of *P. filamentosus* with the remaining 4 receivers placed optimally relative to all deployed receivers to monitor 75 to 400 m depth.

Placement of receiver gates was optimized with respect to the receiver’s probability of detecting a tag transmission over a range of horizontal distances, the bathymetry along the target transect, upper and lower depths the gate needed to encompass, the height of the receiver off the seafloor, desired height of the water column to monitor, the swimming speed of the species, and the minimum acceptable detection rate of the gate. Each receiver was then placed according to an algorithm that functioned as follows: The minimum distance between any two receivers is determined with the following set of equations.

The effective fence height ( is the minimum height of the fence off the seafloor ( minus the height of the receiver from the seafloor (. The receiver’s hydrophone is assumed to be omnidirectional with a detection envelope approximating a sphere, that is, a receiver has an equal probability of detecting a tag for any two coordinate sets that produce equivalent primary transmission path lengths. From this, the algorithm can calculate half the distance between any two subsequent receivers in the fence ( using the effective fence height (, the radial distance at which the receiver’s detection function falls below ½ the minimum acceptable detection rate of the gate using Pythagorean’s theorem and multiplying the result by two, as the spacing between each receiver is two equal hemispheres. The algorithm uses the radius at half the desired detection threshold for inter-receiver spacing because the probability of detection at either receiver is independent of detection at the other, and thus, using the additive property for probability, the total probability of either receiver detecting the transmission is equal to the minimum acceptable detection rate. Receivers are placed so that their line-of-sight distance does not exceed this maximum allowable distance.

The algorithm then calculates the distance between two subsequent nodes of the fence for the minimum acceptable detection rate of the gate was two times that of the desired rate using the same method. This step is important as the detection envelope of receivers at either end of the fence will not overlap, and as such, the probability of detecting a single transmission at either end of the gate is dependent only on the single receiver. Calculating the distance between two receivers with two times the desired detection rate of the gate produces an inter-receiver spacing that is equal to the distance the detection envelope of each of these receivers will monitor.

The algorithm then calculates the distance across the seafloor along the line of the transect by calculating the distance between each bathymetric data point, again using Pythagorean’s theorem. This allows the algorithm to take into account the effect of sloping bottoms where the line-of-sight distance between two receivers is greater than their horizontal distance. The algorithm then positions the two receivers at half the distance determined for receivers with two times the desired detection rate of the gate from either end of the transect. The seafloor distance along the transect between these two receivers is divided by the distance between subsequent nodes calculated using half of the minimum acceptable detection rate and rounded to the next whole integer. This integer is one greater than the receivers required to create the fence, not accounting for the two end receivers whose placements have already been determined. The distance between the end receivers is divided by the required receivers, producing a new inter-receiver spacing that is equal to or less than the maximum spacing determined by equation 2. Receivers are placed at line-of-sight intervals equal to this new spacing between the two ends of the gate. The algorithm then checks to ensure that at no point does the bathymetry along the gate transect interfere with the line-of-sight between any two subsequent receivers.

The algorithm then calculates the minimum interval between subsequent tag transmissions to ensure a tag will transmit while a fish traverses the gate. The plane of intersection at which two spheres intersect forms a circle. A horizontal chord is drawn along the minimum desired fence height. The distance of this chord represents the path through the fence with the lowest likelihood of detection. Multiplying the length of this chord by the swimming speed of the tagged animal gives the minimum time an animal can traverse the gate. The quotient of the minimum time required to traverse the gate, and the tag’s transmission interval gives an estimate of the number of transmissions from a tagged individual along this path. Provided the transmission interval is less the minimum time required to traverse the gate, the individual has a probability of detection greater than or equal to the minimum acceptable detection rate of the gate. The probability of any one transmission from a tag being detected is independent of the one that proceeded it, the probability of detecting an individual at least once as it swims through the gate is equal to the sum of the detection probability of that animal at the point of each transmission. This means that the true detection probability for a tag that transmits multiple times while passing through a gate is significantly higher than the minimum acceptable detection rate of the gate itself. Using this method, we calculated deployment coordinates and depths for each receiver component of the gate and ensure that the probability of detection for an individual along any path is greater than zero.

***Pristipomoides filamentosus* Capture and Tagging**

Between 13 April 2012 and 11 January 2018, 292 individuals of the species *Pristipomoides filamentosus* were tagged in the Makapuu region southeast of the island of Oahu, Hawaii (Figure: tagging locations.png). 240 of these 292 individuals were detected at least one time on the receiver array. Tagged fish ranged in size between 30 and 76 cm (median fork length: 45.5 cm, 1st IQR 41.0, 3rd IQR: 53.0) (Fork Length Hist.png).

Fish in this study were captured with the assistance of commercial fishers using hook and line gear and hydraulic or electric line pullers. Kaka line and make dog rigs are the most common method of bottomfishing in the Hawaiian archipelago and were used to land fish during this study (Anonymous, Hawai’i pelagic handline fisheries: History, trends, and current status; Haight et al 1989). Hooks were baited with squid, anchovies, sardines, and/or saury for bait. When using kaka line rigs, no more than 6 baited hooks were used at a time. Palu, an attractant released when the rig is at fishing depth, consisted of finely chopped bait and an occasionally a filler material such wheat chafe, rice, or oats.

Once aboard the vessel, researchers removed the hook from the fish’s mouth. Fish that were determined to be of acceptable size for tagging were placed in a padded v-board cradle. Oxygenated salt water was pumped over the fish’s gills via saltwater hose or a recirculating pump. If severe symptoms of barotrauma, such as buldging eyes or stomach eversion, were visible, the fish’s swim bladder and/or stomach were punctured with a sterile 18-gauge needle. Fish were then positioned so their ventral side faced researchers.

Swimming performance of teleosts is unaffected by transmitter tags that do not exceed 2-12% of the individual’s body weight (McCleave & Stred 1975, Adams et al. 1998, Brown et al. 1999). To determine the minimum size of a *P. filamentosus* eligible for tagging, a V13 and a V13P tag were each weighed to the nearest ten thousandths of a gram on a mass balance. Using a conservative 2% threshold, the minimum recommended weight for an individual implanted with each tag type using the following equation:

Where is the minimum weight of a fish in grams and is the weight of a tag. The minimum fork length of *P. filamentosus* eligible for tagging was calculated by solving the following allometric growth function to determine the fork length ( corresponding to each minimum weight (.

Parameter estimates used for the normalization constant, , and the allometric scaling exponent, , have been previously determined for *P. filamentosus* and are 38.72 and 0.34, respectively (Uchiyama and Kazama, 2003).

Tags were implanted through an incision, approximately 1.5 – 3 cm in length, made in along the fish’s ventral centerline in the direction of the anteroposterior axis. The incision was closed using sutures (Ethicon PDS\*Plus antibacterial monofilament) and a reinforced surgeon’s knot secured first with a triple throw, then a double throw, and finally a single throw tied in alternating directions. When available, fish were tagged externally, between the lateral line and dorsal fin, with a 4-inch PDS-2 dart tag (Hallprint PTY, inc. Hindmarsh Valley, South Australia). These tags were provided by the Pacific Islands Fisheries Group for identification as part of a longterm conventional tagging program.

***Barotrauma and Predation: Mitigation Stratagies and Assisted Recompression***

Deep 7 bottomfish species are physoclystic, that is, the gas bladder is not open to the gastrointestinal tract. As a result, bottomfish are particularly succeptable to barotraumatic injuries due to rapid expansion of the swimbladder when captured at depth. Effects of barotrauma include organ displacement, internal hemoraging, and embolism. Severe barotrauma may result in organ damage and death. Methodological studies focusing on mitigating barotrauma in deep-water teleosts indicate that slow ascent rates, limited on-deck handling times, and rapid recompression have positive improve survivorship outcomes, but these studies have largely focused on rockfish (genus: *Sebastes*). External symptoms of barotrauma observed during this project included esophageal eversion and exophthalmia due to swimbladder expansion. Rapid air release and deflation of the fish while making the peritoneal incision was not uncommon and likely due to swimbladder rupture.

Predation by sharks, jacks, and marine mammals was also a significant source of mortality. Using SCUBA, four opakapaka were observed for periods of 30-60 minutes after they were lowered to roughly 20 m in a mesh pen (approximately 4ft high, 6.5ft diameter). None of the fish showed observable signs of severe barotrauma, however within 10 minutes, between 2 and 5 sharks were observed swimming near the pen. A number of fish were either totally or partially consumed by predators during ascent and detection of rapid movements throughout the study site during the period immediately after tagging were consistant with the movmenets of tagged sharks in the area and followed by cessation of all movement following tag expulsion. It is likely that palu, used to aggregate bottomfish, also attracted predators, and exacerbated the issue

To reduce mortality in this study, when possible, the rate at which the mainline was pulled was slowed to facilitate some compensative offgassing of the swimbladder during ascent while still pulled at a rate to limit predation. On-deck handling time never exceeded 10 minutes, with the majority of surgeries lasting no-longer than 5 minutes. Various statagies for release were attempted to balance rapid recompression and predator avoidance. Release strategies included release at the seafloor using a drop shot device (Blacktip Brand, 178 individuals), midwater release (30-60 m) using a drop shot device (Seaquilizer Brand, 75 individuals), midwater release (20 m) after acclimating in a holding pen (4 individuals), and surface/near surface release (42 individual). The release method was not recorded for 14 individuals. A novel seafloor release mechanism involving a ventilated cage and with a timer released door was also in development, but a working prototype has yet to come to fruition.

***Analysis***

***Analysis Periods***

Logistical challenges involved in the recovery and redeployment process limited maintenance and turnover of receivers to one or two events per year. It was not uncommon that during maintenance cruises a receiver station was unable to be recovered. Events that limited recovery include failure of the acoustic release, stations that broke free of their moorings, and entanglement with derelict fishing gear or benthic substrate. Failure of a VR2 receiver unit or corruption of the receiver’s data file also resulted in data loss. Of 274 total station deployments, 24 stations (8.76 %) were unable to be recovered or suffered equipment failure resulting in a loss of data.

Attempts were made to maintain the position of individual receiver stations of the planned array throughout the duration of the project however station and data losses resulted in a functional array that varied in structure for each redeployment period. The structure of the network array was also affected by the acquisition and installation of additional receiver stations, to replace those that had been lost and to increase monitoring capacity, acquired during the course of the study. Planned and unforeseen variations in the structure of the functional array throughout the project make it difficult to directly compare observations of tagged individuals across deployment periods. This could be achieved by removing data from all receiver stations not present through full duration of the study but would result in discarding significant data regarding the location of tagged fish during many periods. Rather than attempt to reconcile the data in this way, when appropriate, results from each of 9 analysis periods are presented (FIGURES: FUNCTIONAL ARRAY FIGURES). Analysis periods were defined by the periods between subsequent redeployments of the full receiver array beginning at 00:00 the following day and ending at 23:59 the day prior to retrieval.

Specific hypotheses require data from particular stations for analysis. Loss of receiver stations constituting receiver fences to the north and south of the BRFA limit conclusions that can be drawn regarding the frequency of movement and time individuals were located within or outside reserve boundaries, as an individual may have left the area undetected. Other hypotheses, such as home range size, do not require particular stations, but it is worth noting that the size of the home range calculated is ultimately dependent on the placement and positioning the receivers on which each animal was detected and thus changes to the functional network between analysis periods may affect calculations of home range size.

***Post-Release Mortality***

Early analysis of collected data indicated a high post-release mortality rate for tagged *P. filamentosus*. High mortality rates likely stem from heavy predation of tagged fish by sharks and cetatians, and other predators, as well as barotrauma during ascent. The status of each tagged fish was determined using detection records and the following algorithm (FIGURE TRACK STATUS ALGORTHM). Only fish with detection records greater than 14 days were considered for further analysis. Fish that were detected moving between receiver stations with non-overlapping detection ranges were considered alive. If the fish was not detected moving but did possess a depth sensor, the fish was considered alive if, after 14 days, it’s depth range exceeded 10 m. This range was selected to eliminate tidal effects on water column depth. If a tag did not have a depth sensor and was not detected moving after 14 days, it was classified as dead if it was detected on 3 or more receiver stations during the first 14 days at liberty. Sharks tagged with acoustic transmitters moved regularly throughout the study area and were detected frequently on multiple stations. Rapid movement followed by a prolonged period of constant detection / constant absence observed in tags were presumed to be fish consumed by sharks or other predators that later expelled the tag within or outside the detection radius of a receiver. Fish that were not classified alive or dead were grouped together in a third uncertain category.

***Testing Hypotheses***

Hypothesis 1 was tested by calculating the maximum linear range for all individuals. Because Deep 7 bottomfish habitat is defined by a depth band along a slope, bathymetric topography can introduce bias in this estimation. To mitigate this, the distance between all stations an individual was detected was calculated using a depth-constrained least cost path algorthm and 50 m bathymetry data. Maximum and minimum depths were constrained by the range recorded by depth tags from fish believed to be alive. Path lengths between all locations a fish was detected were calculated with maximum linear homerange defined as the length of the largest of depth constrained path.

The maximum linear range for all individuals was compared to the linear habitat dimension within each of the 12 BRFAs. For 11 of the 12 BRFAs, this was determined by using the least cost path algorithm constrained between 100-400 m (bottomfish EFH) to move along the contour from one side of the BRFA to the other. Path start and endpoints along the BRFA’s boundary corresponded to a depth of 128 m, the average hooking depth for *P. filamentosus* reported in the Northwestern Hawaiian Islands (Kelly & Moriwake, 2012). For the linear habitat dimension of BRFA H, which is entirely within the depth bounds of Bottomfish habitat, the corner to corner length was used.

Hypothesis 2 was tested by determining if location coordinates for each tag detection occurred within our outside BRFA boundaries. Movement across BRFA boundaries was said to occur when a tag was detected outside of BRFA boundaries followed by a detection within BRFA boundaries, or vice versa. The number of movements across BRFA boundaries was then standardized by the time at liberty, the number of days elapsed between tagging and the final detection of a tag.

***Results***

**Analysis Periods**

Only during the last of the 10 analysis periods, were enough fish present to make it worthwhile to analyze data…

**Fish Tagging and Post-release Mortality**

Hypothesis 1: Home Range Size

Hypothesis 2: Movements across BRFA Boundaries

Hypothesis 3: Uniform habitat use