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# Detection, Classification and Prediction of Satellite Tagged Marine Mammals for the U.S. Navy

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*Mission Development Branch  
Space Systems Development Division*

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| 14. ABSTRACT<br>As stewards of the sea, the United States Navy is committed to protecting the environment while defending freedom. In recent years, marine mammal researchers have observed and reported an increase in vessel strikes, mortality rates, enigmatic standings, and fishing gear entanglements, particularly among baleen whales. Integrating marine mammal localizations into U.S. Navy Maritime Domain Awareness (MDA) systems will provide the warfighter with the ability to detect, predict, and respond to marine mammals that reside in the maritime battlespace. An MDA system must be able to accurately interpret and predict marine mammal's movement in order to provide meaningful alerts to nearby vessels. Satellite-tracking tags have become an increasingly popular tool to track, study migration routes, produce habitat density models, and assess population abundance among marine mammals. Tag data is transmitted to the Argos satellite constellation, reported to the user on the Argos Web Portal, and optionally published on open sourced repositories. This paper explores the positional fidelity of a Wildlife Computers SPOT-303C tag and Wildlife Computers SPOT-258F, two popular tag models used by marine mammal researchers. Tag data was collected from Argos Web Portal, the Collecte Localisation Satellites (CLS) RXG-134/Goniometer receiving system, and Great Scott Gadget's HackRF One Software-Defined Radio (SDR). A Naval Research Lab (NRL) vessel was affixed with the SPOT-258C and SPOT-303C tags and performed a series of runs to simulate marine mammal behavior. Significant positional errors were found in Argos Web and RXG-134/Goniometer data during the vessel test. Argos processed tag data and RXG-134/Goniometer directions should be used as marine mammal presence-only detections. If the U.S. Navy intends to leverage these sources, prior knowledge of the species behavior and the Particle Filter (PF) algorithm provides a general marine mammal movement model. The HackRF SDR provides a cost-efficient alternative for capturing marine mammal tag transmissions. A series of Hidden Markov Models (HMMs) was applied to the vessel test data in order to identify marine mammal like behaviors. A 4-state HMM can accurately distinguish complex marine mammal behaviors such as sudden turns, transiting, or meandering. Finally, a stochastic state space Unobserved Component (UC) model was applied to the vessel test data in order to predict and forecast movement behavior. The UC model is able to interpolate gaps in time series and forecast future time steps using harmonic trends observed in the time series. Marine mammal tag data is nonlinear, sparse, and prone to measurement error; conditions that are ideal for the UC model. If the U.S. Navy intends to use marine mammal satellite-tracking tags for detection, prediction, and avoidance planning, error, uncertainty, and data collection method must be considered. The U.S. Navy should leverage existing signal receiving systems, like the HackRF SDR, to detect marine mammal tag transmissions. The HMM's behavioral state classification and UC model's prediction and forecasting capabilities are intuitive and biologically meaningful to U.S. Navy personal, many of which are naïve to marine mammal ecology. These models will assist U.S. Navy decision making while encountering marine mammals in the maritime battlespace. |                        |                              |                                       |                                                                        |                                                           |
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## EXECUTIVE SUMMARY

As stewards of the sea, the United States Navy is committed to protecting the environment while defending freedom. In recent years, marine mammal researchers have observed and reported an increase in vessel strikes, mortality rates, enigmatic **standings**, and fishing gear entanglements, particularly among baleen whales. Integrating marine mammal localizations into U.S. Navy Maritime Domain Awareness (MDA) systems will provide the warfighter with the ability to detect, predict, and respond to marine mammals that reside in the maritime battlespace. An MDA system must be able to accurately interpret and predict a marine mammal's movements in order to provide meaningful alerts to nearby vessels. Satellite-tracking tags have become an increasingly popular tool to track, study migration routes, produce habitat density models, and assess population abundance among marine mammals. Tag data is transmitted to the Argos satellite constellation, reported to the user on the Argos Web Portal, and optionally published on open sourced repositories. This paper explores the positional fidelity of a Wildlife Computers SPOT 303C tag and Wildlife Computers SPOT 258F, two popular tag models used by marine mammal researchers. Tag data was collected from the Argos Web Portal, the Collecte Localisation Satellites (CLS) RXG-134 Goniometer receiving system, and Great Scott Gadget's HackRF One Software Defined Radio (SDR). A Naval Research Lab (NRL) vessel was affixed with the SPOT 258C and SPOT 303C tags and performed a series of runs to simulate marine mammal behavior. Significant positional errors were found in Argos Web and RXG-134 Goniometer data during the vessel test. Argos-processed tag data and RXG-134 Goniometer directions should be used as marine mammal presence-only detections. If the U.S. Navy intends to leverage these sources, prior knowledge of the species behavior and the Particle Filter (PF) algorithm provides a general marine mammal movement model. The HackRF SDR provides a cost-efficient alternative for capturing marine mammal tag transmissions. A series of Hidden Markov Models (HMMs) was applied to the vessel test data in order to identify marine mammal like behaviors. A 4-state HMM can accurately distinguish complex marine mammal behaviors such as sudden turns, transiting, or meandering. Finally, a stochastic State Space (SS) Unobserved Component (UC) model was applied to the vessel test data in order to predict and forecast movement behavior. The UC model is able to interpolate gaps in time series and forecast future time steps using harmonic trends observed in the time series. Marine mammal tag data is nonlinear, sparse, and prone to measurement error—conditions that are ideal for the UC model. If the U.S. Navy intends to use marine mammal satellite-tracking tags for detection, prediction, and avoidance planning, then error, uncertainty, and data collection method must be considered. The U.S. Navy should leverage existing signal receiving systems, such as the *HackRF* SDR, to detect marine mammal tag transmissions. The HMM's behavioral state classification and UC model's prediction and forecasting capabilities are intuitive and biologically meaningful to U.S. Navy personnel, many of which are naïve to marine mammal ecology. These models will assist U.S. Navy decision making while encountering marine mammals in the maritime battlespace.

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# DETECTION, CLASSIFICATION, AND PREDICTION OF SATELLITE TAGGED MARINE MAMMALS FOR THE U.S. NAVY

## 1. INTRODUCTION

### 1.1 The Jermon and Isabella Karles Fellowship Program

On 18 June 2008, the United States Naval Research Laboratory (NRL) established the Jerome and Isabella Karle Distinguished Scholar Fellowship Program in honor of the late Drs. Jermon and Isabella Karle. Drs. Jermon and Isabella Karle made many remarkable contributions to the chemistry field, including methods for analyzing X-ray diffraction, advancements to determine X-ray crystal structures, and techniques for extracting plutonium chloride in support of the *Manhattan Project*. Dr. Jermon Karle earned the prestigious Nobel Prize in Chemistry for his work in X-ray diffraction in 1985. Those accepted into the Jerome and Isabella Karle Distinguished Scholar Fellowship Program are encouraged to embody the same fervor for innovation in their own research projects. Research projects last no more than 24 months and are funded internally.

NRL's Naval Center for Space Technology (NCST) accepted a Karles Fellowship nomination to develop advanced approaches for monitoring marine mammal populations and interactions with humans on 7 August 2017. By authority of the Marine Mammal Protection Act (MMPA), marine mammals are protected by law. In compliance with the MMPA, the U.S. Navy strives to prevent harm to marine mammals. This requires that the U.S. Navy to be able to detect and avoid marine mammals in the battlespace environment, and be able to monitor the long-term effects of U.S. Navy's exposure on marine mammals.

The U.S. Navy monitors worldwide vessel-traffic for Maritime Domain Awareness (MDA) initiatives. While MDA systems expertly monitor vessel traffic and systems exist that attempt to monitor marine mammal populations, there is no single system that can handle both vessel tracking and marine mammal habitat monitoring together. This research develops a merged operational picture and predictive algorithms for the interactions between mammals and vessels. It is vital to assess the fidelity of space-based marine mammal tracking assets prior to integrating data into operational vessel tracking systems. Therefore, a thorough error analysis of poorly conditioned, time out-of-phase marine mammal tracking data is offered. The work builds from existing work in Code 8110, including NRL's MDA system (Sealink-Advanced Analysis (S2A)) and develops future sensor capability to enhance the detection of mammals. Experiments and analysis were conducted at NRL's Washington D.C. headquarters and Chesapeake Bay Detachment, and commenced 7 August 2019.

### 1.2 The U.S. Navy and Marine Mammals

The U.S. Navy operates in nearly every body of water in the world, covering 70% of the Earth's surface. Forty-nine different species of marine mammal call these bodies of water home: 3 otter (*Lutrinae*) species; 1 polar bear (*Ursus maritimus*) species; 4 manatee and dugong (*Sirenia*) species;

13 seal and sea lion (*Pinnipeds*) species; and 28 whale, porpoise, and dolphin (*Cetacea*) species (Status of Marine Mammal Species and Populations, 2019). Species whose stocks are depleted or are in danger of extinction are reported as endangered by the Endangered Species Act (ESA) (1973). Periodic marine mammal stock assessments are required by the Marine Mammal Protection Act (MMPA) (1972). The law emphasizes the value of marine mammals to our ecosystem and economy. Protective and conservation measures are required in the event a stock shows sign of decline (Marine Mammal Protection Act, 1972).

Anthropogenic factors, such as illegal, unreported, and unregulated (IUU) fishing contribute to the decline of marine mammal stocks (Laist et al, 2001). By recommendation of the Presidential Task Force on Combating IUU Fish and Seafood Fraud in Recommendation 8 “Enforcement—Information Sharing” and by the authority of the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (MSRA), the U.S. Navy is obligated to strengthen international fisheries management organizations and to address IUU fishing and bycatch of protected living marine resources, particularly with dragged nets that entangle whales.

By authority of the ESA, the MMPA, the Presidential Task Force on Combating IUU Fish and Seafood Fraud, and the MSRA, the U.S. Navy is obligated to support conservation efforts aimed to protect and revive stocks of endangered species. Historically, the U.S. Navy has had a number of highly publicized incidents regarding marine mammals. A 2013 report conducted by the Space and Naval Warfare Systems Center Pacific (SPAWAR) lists five mass marine mammal stranding events potentially associated with Navy sonar activities between 1996 and 2006 (Marine Mammal Strandings Associated with U.S. Navy Sonar Activities, 2013). These stranding events are defined by marine mammals washed ashore, dead or alive, unable to return to their natural habitat. Anthropogenic stranding cases can occur due to fisheries interaction, marine mammal viewing, ingestion of marine debris, toxic pollution, acute noise exposure, and vessel vessel strikes. Large whale vessel strike data collected over a 27-year span identified Navy, container, cargo, and freighter vessels as the most frequent vessels involved in whale vessel strike incidents (Large Whale Ship Strike Database, 2003). Navy vessels involved in whale vessel strike incidents include a submarine traveling at the surface, a frigate, a heavy cruiser, aircraft carrier, destroyers, and hydrofoils (*USS Aquila*, 2019). In one vessel strike incident involving the Navy hydrofoil, *USS Aquila*, the whale was severed into three pieces; the vessel stern hall was warped; and crew members required medical attention.<sup>7</sup>

The Navy must protect the environment while engaging in military readiness training and testing exercises. There are twelve Operations Areas (OPAREA) defined in the Atlantic and the Gulf of Mexico for at-sea Naval exercises (Fig. 1). For each OPAREA, the MMPA regulates and authorizes the incidental take of marine mammals to Navy training and testing activities. Given that citizens are engaging in lawful activities, MMPA Letters of Authorizations (LOA) authorize marine mammal take for up to five years. The John S. McCain National Defense Authorization Act (NDAA) for Fiscal Year 2019 extended the MMPA LOAs to seven years for the Navy’s Atlantic Fleet Training and Testing (AFTT) Study Area (United States Fleet Forces Command, 2019). The additional two years include a year with maximum level of training and testing activities and another with representative training and testing activities. A throughout analysis of distributions of marine mammals in the AFTT Study Area, a review of training and testing activities, and a technical risk assessment to determine the likelihood of effects on marine mammals were required prior to seven-year extension approval. Each Naval training exercise is identified, quantified by perceived stress on marine mammal population, and given a maximum number of activities across a seven-year span. For example, in the AFTT Study Area, 35 Maritime Security Operations involving Anti-Swimmer Grenades are allotted for the Virginia Capes OPAREA. Just 371 Mine Countermeasure activities using active sonar are allotted for the Virginia Capes OPAREA. These exercises are just two of the 36 exercises outlined in the MMPA LOAs. All 36 exercises involve acoustics and/or explosives, which are both known to have adverse effects on marine mammal populations.

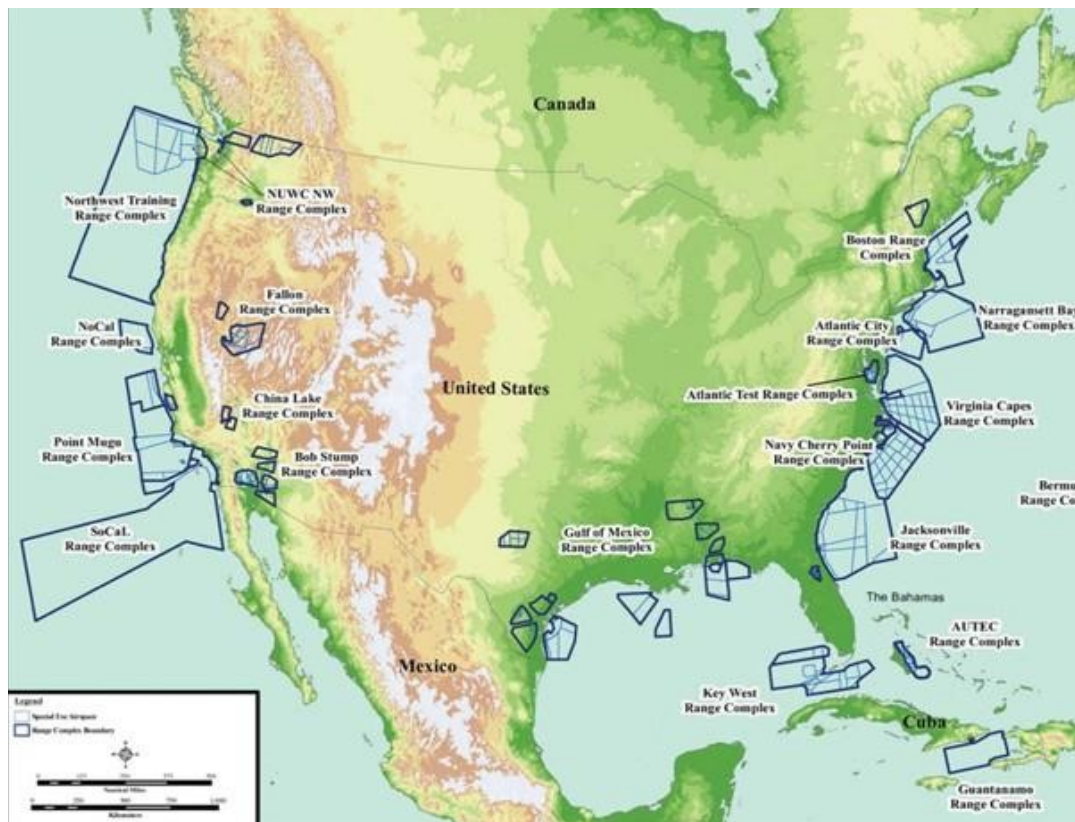


Fig. 1—U.S. Navy OPAREA

Two Navy programs conduct marine mammal monitoring initiatives to ensure the fleet is complying with the MMPA and preventing incidental take. The Chief of Naval Operations Energy and Environmental Readiness Division (OPNAV N45) supports research on the potential impacts on marine species due to Navy activities through the Living Marine Resources (LMR) program. The LMR program is managed by Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) and invests in occurrence, response, exposure, and consequence studies related to marine mammals and Navy activity (LMR News, 2019). The Marine Mammals and Biology (MMB) program sponsored by Office of Naval Research (ONR) also funds marine mammal research; specifically, research focused on monitoring and detection, integrated ecosystem, model and database development, and effects of sound on marine life (Marine Mammals and Biology Program, 2019). The above programs have provided a greater understanding of Naval activities impacts on marine mammals. Understanding and awareness of marine mammal species not only protects animals from inadvertent harm, but supports the Navy's commitment to Maritime Domain Awareness (MDA) initiatives.

### 1.2.1 Maritime Domain Awareness (MDA)

In the mid-90s to early 2000s, maritime platforms and contacts of interest were tracked manually, roughly amounting to 400–600 tracks produced daily. The Information Age has brought rise to an exponential increase in number of maritime platforms and contacts. Strategic Operational and Tactical commands must make sense of these contacts and platforms in order to make informed, timely decisions. In response to the mass influx of maritime data, the U.S. established the conceptual framework of MDA. MDA is an U.S. effort to strengthen effective understanding of the maritime domain that could impact safety, economy, and environment (Navy Maritime Domain Awareness Concept, 2007). Automated

MDA systems have been developed to aggregate, fuse, and track surface contacts such as Automatic Identification Systems (AIS). The NRL's Sealink Advance Analysis (S2A) is just one example of the many MDA systems available (Section 1.2.2).

The MDA initiative was established well before the turn of the century. Prior to 2007 MDA was achieved through mixed arrangements and non-standardized procedures. To address inadequacies in MDA procedures, the MDA Concept of Operations (CONOPS) was established to outline agency roles, responsibilities, and information sharing processes (NMIO, 2007). The Department of Navy (DON) was tasked with developing an information architecture to encourage information sharing, communication, collaboration, and coordination across agencies. The DON aimed to have the concept fully implemented within ten years. Although MDA has surpassed expectations in most aspects of maritime domain, it is lacking on the environmental front. Environmental data such as oceanographic and meteorological variations, fishing activity, and seasonal variations in marine life have not been fully integrated in current MDA systems. Seasonal migratory routes, critical feeding areas, rookeries, and stocks are provided by the MMPA and should be integrated into MDA systems to support effective understanding of the environment.

### 1.2.2 Leveraging Sealink Advance Analysis (S2A) for Marine Mammal Monitoring

S2A is a comprehensive maritime system that provides an end-to-end MDA capability. These capabilities include, but are not limited to, multiple input vessel data fusion; user-definable alerting; automated alerting for anomalous vessel behavior and areas of interest; and vessel track database sorting. S2A produces over 700K active vessel tracks worldwide, and every day S2A's vessel database comprises a variety of sources: Maritime Safety and Security Information System (MSSIS); open-source, commercial data; satellite Automatic Identification Systems (AIS); and other sources such as the surveillance network of radar towers and infrared cameras along the Chesapeake Bay (Fig. 2). On S2A's interactive map, vessel locations are colored based on data source. The vessel data is aggregated, stored, and visualized by user-defined queries. S2A is a mature software capability with many functional components.

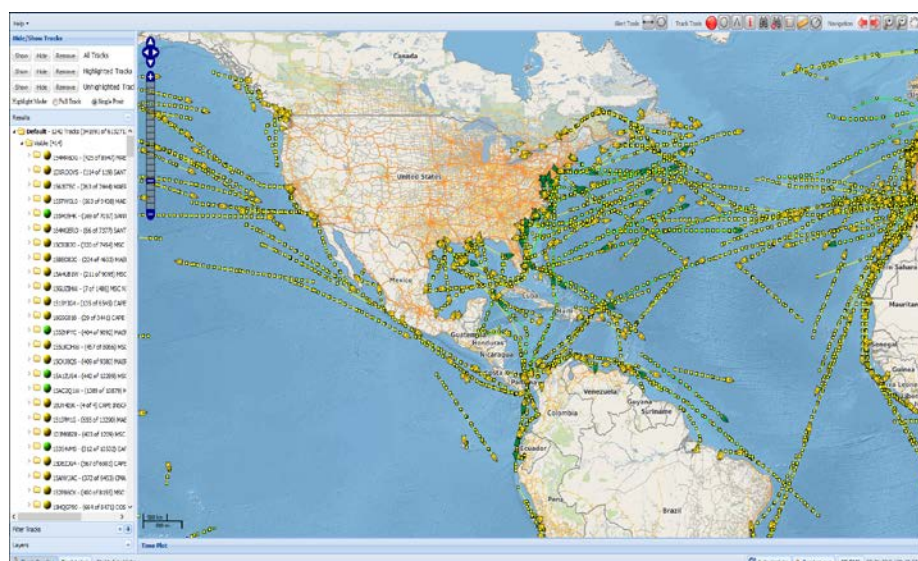


Fig. 2—S2A interactive map of vessel tracks over a week. Yellow tracks are generated from AIS sources and green tracks are generated from mixed sources. The left panel lists first 25 vessel tracks by MMSI.

S2A users have the ability to query the vessel database based on their research interest. One can define geographic boundaries, search vessels within that boundary, and set tripwires for real-time, automatic alerts of vessels that enter an area. Regions of interest for marine mammals might include Seasonal Management Areas (SMA) along the U.S. East Coast (Fig. 3). Due to the prevalent vessel strikes seen among North Atlantic right whales, NOAA Fisheries has established seasonal speed restrictions for vessels 65 feet or longer in historically critical areas used by the North Atlantic right whale (NOAA Fisheries, 2013). One can import SMA shapefiles into S2A, query for vessels previously or currently in the region, and set automated alerts for vessels violating the seasonal speed restriction. The Chesapeake Bay is home to the Baltimore and Hampton Roads ports. Due to the high volume of vessel traffic, an SMA has been established permitting vessels to travel over 10 knots (kts) from November 1<sup>st</sup> to April 20<sup>th</sup>. S2A can be leveraged to identify vessels violating this speed restriction and prevent any inadvertent collisions with marine mammal species in the area during this time.

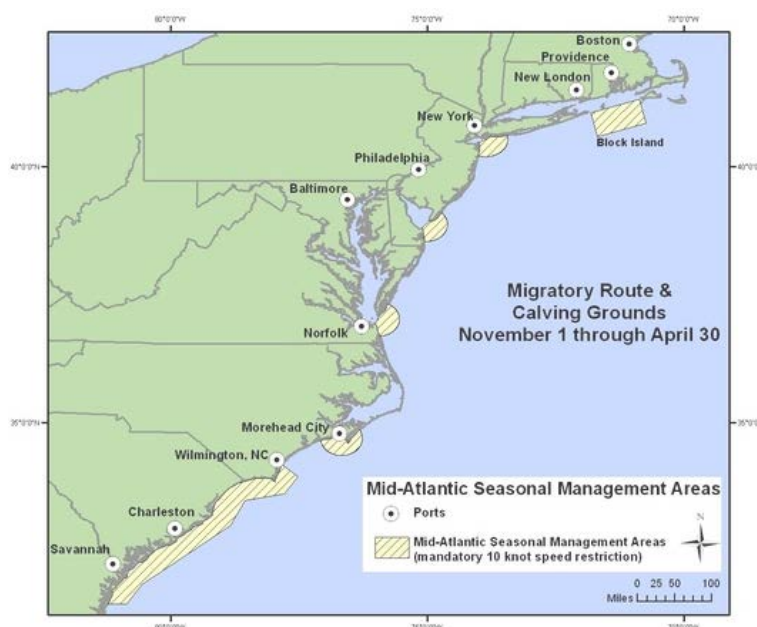


Fig. 3—SMAs to reduce vessel strikes of large whales

The S2A vessel track database dates back to May 2017. S2A has been used to investigate unusual mortality events in large whales. On 31 January 2019, HDR Inc. and NAVFAC Atlantic deployed satellite telemetry tags on humpbacks for the Mid-Atlantic Humpback Review study. In February 2019, a tagged humpback was found washed ashore, dead on the North Carolina beaches. Satellite-telemetry data prior to 17 February 2019 showed the tagged whale was active just off the coast of the Cape Henry lighthouse. The S2A database was acquired and uncovered 16 unique vessels were reported in the whale's vicinity in its last active hours. The whale's tag location was layered in S2A and a vessel activity playback feature was used to visualize vessel movement and tagged humpback movement. A fishing vessel, vehicle carrier, bulk carrier, coast guard vessel, and surfaced submarine all came within one nautical mile of the tagged humpback location. Given the noisy nature and uncertainty of satellite-telemetry data, the cause of the humpback death could not be concluded as vessel strike. Detailed error analysis is required to determine probable location range of the tagged humpback.

### 1.2.3 Significance of Problem

The U.S. Coast Guard, the National Marine Fisheries Service (NMFS), and the Fish and Wildlife Service are the lead government agencies responsible for enforcement of the MMPA, the ESA, and the Marine Protection, Research and Sanctuaries Act (Protecting America's Fisheries, 2017). The latter has established marine sanctuaries around the country since 1972. While these agencies regularly and successfully conduct at-sea boardings to identify illegal fishing practices, patrol Exclusive Economic Zones (EEZs), enforce speed restrictions, and provide funding for Early Warning Systems (EWS) to notify presence of the endangered species, marine mammal stocks are still declining.

As of spring 2019, over 70% of all whales, porpoise, and dolphin species are listed as endangered. Of the 49 marine mammal species, 30 marine mammal species are endangered (Status of Marine Mammal Species and Populations, 2019). The vaquita and North Atlantic right whale are the closest to extinction. The vaquita is victim to illegal gillnet fishing and poaching by Chinese fisherman for the vaquita's highly sought swim bladder (Jefferson, 2019). It is estimated there are less than 10 individuals left.

The North Atlantic right populations were decimated by whaling practices until the end of whaling in the 1980s. Today there are no more than 425 individuals (SAVE Right Whales Act, 2019). Before whaling's height, it was estimated the population reached over 10,000 individuals in the Atlantic Ocean alone. Field studies and necropsy reports show the North Atlantic right whale is threatened by vessel strikes; fishing gear entanglement, particularly sinking ground lines; and unexplained low birth rates among females. The status of the North Atlantic right whale has become so dire that Massachusetts congressman, Seth Moulton, proposed the "Scientific Assistance for Very Endangered North Atlantic Right Whales Act of 2019," or the "SAVE Right Whales Act," in March 2019. This bill aims to minimize conflicts between North Atlantic right whales and human activities by initiating conservation programs and providing financial support.

Ocean dynamics, shipping traffic, seismic air gun surveys, geophysical processes (e.g. wind or rain), and marine life movement and vocalizations all contribute to what is known as the underwater soundscape (Miksis-Olds, 2018). The increase of shipping traffic and human activity in the ocean has overwhelmed ambient noise levels in the underwater soundscape. An increase in ambient noise levels due to human activity has adverse effects on echolocating marine life's behavior and ability to decipher prey location, orientation, and range. The Natural Resources and Defense Council and International Fund for Animal Welfare released a 2016 film, *Sonic Sea*, to bring light to human's contribution to ocean noise and the effects on marine mammals. The film criticizes Navy's use of high and mid frequency active sonar by referencing two marine mammal mass stranding events (Haro Strait and the Bahamas) which were suspected to be a result of Navy sonar (Dougherty & Hinerfeld, 2018). Controlled sound exposure studies among marine mammals have shown animals behaving unusually in the presence of sonar: animals stopped feeding, stopped calling, and abruptly surfaced. When deep-diving, marine mammals surface too quickly; it is believed that the animals suffer from decompression sickness, similar to when scuba divers' surface too quickly (Woods Hole Oceanographic Institution, 2018). Necropsy reports from stranding events report high nitrogen levels in the bloodstream and tissue, a sign of decompression sickness.

In response to these stranding events, researchers have become interested in received noise and hearing levels among marine species. Auditory sensitivity changes and hearing abilities for marine mammal species have been well documented and steps to calculate the cumulative received exposure have been offered for regulatory agencies to implement (Southall et al., 2007 & 2019). There is a lack a research in long-term effects of increased ambient noise due to human activity on species. Naval MDA systems should implement suggested marine mammal noise exposure criteria for long-term monitoring of residual hearing effects. This requires active marine mammal tracking capabilities and documentation of

U.S. Navy fleet movement and sonar use. These sound and marine mammal monitoring capabilities will provide a clearer picture on the Navy's impact on marine mammals.

### 1.3 Existing Marine Mammal Monitoring Efforts

For the U.S. Navy, passive acoustic technology, aerial surveys, shipboard and aided visual surveys, and satellite tagging are some of the most widely used field methods to detect and observe marine mammals. Abundance models, habitat distribution, species call classifications, and state-space track analytics have been applied using these field methods in order to understand how marine species navigate their environment.

Traditionally, aerial and shipboard surveys are the most direct methods for monitoring marine mammal populations. Aircrafts and vessels follow the line transect method when conducting visual surveys. Coastlines are divided into transect lines, humans identify and count marine mammals along the transect lines, and the process is repeated until the minimum number of samples is met to provide a population density estimate for the area. Factoring flight hours, fuel, and man power, this method of marine mammal monitoring can be costly and limited to areas near shore.

Shipboard surveys are conducted before, during, and after Naval training exercises by Navy Watch personnel. Navy Watch personnel, including bridge watch; Commanding Officers; Executive Officers; maritime patrol aircrews; anti-submarine warfare helicopter crews; and civilian equivalents, must undergo Marine Species Awareness Training (MSAT) (Introduction to the U.S. Navy Afloat Environmental Compliance Training Series, 2007). MSAT provides the necessary skill to identify any disturbances on the surface (e.g. tail flukes, marine mammal breaching, dorsal fins) (Fig. 4). Sailors obtain basic knowledge of protected species and the Navy's responsibility for environmental protection through this training. The absence of evidence does mean evidence of absence. Marine mammals can remain underwater for half-an-hour or more, equating to 10–20 percent of their time at the surface (Humane Society, 2019). Even if Navy Watch personnel have a 100% detection rate of marine mammal surface activity, the Navy Watch cannot be certain of where marine mammals are located 80–90 percent of their time underwater. During a visit to Naval Air Station Patuxent River, the P-8 and Seahawk squadron confirmed that prior to deploying sonobuoys, the pilots must confirm there are no marine mammals in the area. The search time for marine mammals cost the Navy not only time otherwise spend conducting the exercise, but fuel and money (Fig. 4). The Scientist to Sea program offered another opportunity to interact with sailors regarding MSAT protocol and practices. While underway on the CG-53 *USS Mobile Bay*, sonar technicians explained that when a marine mammal is heard in the sonar room or observed from watch, the exercise, regardless if active sonar is involved, must cease for a period a time until the marine mammal is perceived to be out of the operating area (Fig. 4). While underway, masses of pinnipeds lounged on coastal areas and cetaceans frolicked on the bow waves of vessels. Marine mammals were observed every day at all nearly all hours. It is inevitable a U.S. Navy vessel will encounter a marine mammal while underway and it is evident the U.S. Navy's spends precious time and money ensuring that marine mammals are unharmed.



Fig. 4—Clockwise from upper left: (i) Naval sonar technicians conducting an anti-submarine warfare exercise, (ii) U.S. Navy helicopter deploying a sonobuoy, (iii) DDG-60 *USS Paul Hamilton* approaching a marine mammal, and (iv) Navy watch personnel searching horizon for marine mammal presence

Passive acoustic technology has given researchers a glimpse of subsurface marine mammal life. Hydrophone arrays passively record the underwater soundscape and recordings can be mined for distinct marine mammal vocalizations. The U.S. Navy maintains an array of 93 hydrophones covering 1,000 square kilometers in the Tongue of the Ocean, located in the Bahamas near the Atlantic Undersea Test and Evaluation Center (AUTEC) and equipped with Marine Mammal Monitoring (M3R) technology. The M3R is capable of acquiring, detecting, and localizing marine mammal calls in near real-time. This system allows the Navy to remotely calculate the abundance of marine mammals on the Navy range and assess behavioral changes of species during naval activity (Jarvis, et al., 2014). The M3R system is also installed in the 178-hydrophone array on Southern California Offshore Range (SCORE) and the 219-hydrophone array on Pacific Missile Range Facility (PMRF). The MMPA authorizes the incidental take of marine mammals for maritime activities. On Navy ranges, such as AUTEC, the Navy Acoustic Effects Model (NAMEO) is used to estimate incidental take of marine mammals for all planned naval exercises (Fetherston, 2019). Exercise scenarios are built onto virtual maps and historically-based species distributions are then layered. The environment and acoustic components of the scenario are then simulated. The simulation then provides a risk assessment of how many incidental takes the exercise may cause. The NAMEO ensures that the Navy is complying with the MMPA; however, it is a preventive system and does not guarantee takes will not occur once the exercise is approved. A real-time system dependent on online marine mammal data rather than historical marine mammal data is preferable.

Other research groups attempt to detect and localize marine mammals via passive acoustics. Moored buoys with autonomous real-time marine mammal detection capabilities have been used to monitor large whale activity in busy shipping lanes. On 20 February 2019, the Woods Hole Oceanographic Institution (WHOI) deployed a buoy in the New York Bight to detect four baleen species by call type: sei, fin, North Atlantic right, and humpback whales (Baumgartner, 2019). Detection data is documented and available in near real-time on WHOI website. The three-year cost to build and maintain a real-time buoy is roughly \$454,000, \$250,000, and \$250,000 for each year. The Maryland Department of Natural Resources and the Maryland Energy Administration have requested a buoy installation to monitor the effects of a windfarm off the coast of Ocean City, MD, on marine life. Low-cost acoustic marine mammal monitor systems are also available. Hydrophones at a commercial cost of \$5,000 can be placed

in an array to monitor time difference of marine animal arrival, and marine mammal call detection and location. However, this requires that researchers consistently retrieve and process archived data collected on each hydrophone.

Acoustic monitoring of marine mammals for detection and location purposes is expensive and requires expertise in underwater acoustics of species call types. Satellite telemetry tags are temporarily attached to marine mammals to provide animal movement measurements. Transmitters, typically on the VHF band, communicate with Earth-orbiting satellites and animal location is either reported or calculated by radio direction finding. These tags can be equipped with an array of sensors including depth, temperature, and video capture capability. Since 2013, LMR has funded several projects that use tagging methods: seven in the Atlantic region and nine in the Pacific region (Marine Species Monitoring, 2019). A tag study involving 15 tag deployments can cost between \$200,000 and \$240,000 and can take 15–20 field days to deploy all tags. More information regarding satellite-telemetry tags for marine mammal monitoring can be found in Section 3. A large portion of tagging studies are generated by academia and independent research organizations. The University of California-Santa Barbara, the University of San Diego, Oregon State University, Duke University, the University of North Carolina Wilmington, Dalhousie University, St. Andrews University, the New England Aquarium, the Cascadia Research Collective, and the Woods Hole Institute are some of the most well-renowned and most-cited marine mammal science institutions in the world.

The National Oceanic and Atmospheric Administration (NOAA) contributes to marine mammal research via extensive marine mammal monitoring efforts. Annual aerial and vessel surveys are conducted in order to evaluate the status of marine mammals. The MMPA hold NOAA responsible for developing stock assessment reports and conservation plans for endangered species (1972). NOAA works intimately with partner nations and U.S. organizations to investigate MMPA violations, establish marine mammal stranding networks, and manage marine mammal take permits (NOAA, 2019). NOAA also coordinates outreach programs to encourage citizen science initiatives. The National Marine Sanctuaries and NOAA invites the public to participate in visual surveys through the annual Sanctuary Ocean Count. Each year, volunteers travel to marine sanctuaries such as the Hawaiian Islands National Marine Sanctuary to count large whales and marine life (Hawaiian Islands Humpback Whale, 2010). Results from mass visual survey efforts are published for easily accessibility.

A successful marine mammal research collaboration effort is the Whale Watch program, which is the most advanced modeling of the blue whale geographic range (Hazen et.al., 2016). Leveraging space-based assets and marine mammal tags attached to blue whales, Whale Watch produces dynamic, monthly predictive models of the whale's geographic range off the U.S. west coast. A majority of these tagging efforts were conducted by Bruce Mate from Oregon State University. The Whale Watch probabilistic models are freely available on NOAA's website. The models are displayed in the form of heat map images that can be downloaded in comma-separated variable files. MDA systems such as S2A can incorporate these models as map layers for marine mammal situational awareness. Naval vessels operating in the Pacific could utilize the monthly Whale Watch models by adding them as map layers in S2A; however, naval vessels need timely marine mammal locations in order to swiftly avoid harm to marine mammals. The Navy would benefit by incorporating near-real time individual locations of *all* marine mammal species in S2A.

#### **1.4 Research Questions and Hypotheses**

Naval entities, the U.S. Intelligence Community, and other government and foreign entities currently use S2A. S2A developers are interested in how S2A can be leveraged to other research communities, such as the marine mammal community. This report investigates available marine mammal data and how marine mammal data should be integrated in U.S Navy MDA systems, such as S2A, for marine mammal

situational awareness. Marine mammal tag data is a popular tool for tracking among researchers, but can be sparse, unreliable, and untimely. Navy personnel must question the accuracy, specificity, and sensitivity of marine mammal tag data. Is marine mammal tag data a reliable data source of real-time marine mammal proximity alerts for the U.S. Navy?

MDA analysts and Navy personnel have little knowledge of marine mammal habitat, behavior, seasonal distributions, and occurrence. If marine mammal information were integrated in an MDA system, how could the system provide biologically intuitive descriptions of the marine mammal movement? What track behavior analytics are available to assist the analyst in understanding the behavior of marine mammals? Finally, how can marine mammal movement be forecasted in order to predict and generate timely alerts for vessel operators? Implications of this research include vessel strike prevention, long and short-term sound exposure monitoring, and vessel enforcement for marine mammal protection.

## **2. APPROACH**

For the remainder of this report, only marine mammal tag data will be discussed. A detailed overview of various types of marine mammal tags, tag message construction, satellite system message processing, and open-source tag data repositories is offered in Section 2.1. Tag data was either processed by the Argos System or collected directly using Software Defined Radios (SDRs) and Collecte Localisation Satellites (CLS) America RXG-134 Goniometers (radio direction finder). System descriptions of each collection method can be found in Section 2.2. Knowledge of how marine mammal tag data is collected and processed is vital prior to applying classification and prediction algorithms. Matrix Profiles (MP) transformations can be used to identify motifs (i.e. patterns) and anomalies in a marine mammal tag time series. Hidden Markov Models (HMMs) were used to classify behavior within marine mammal tag tracks. A stochastic State Space (SS) Unobserved Component (UC) model leveraged Dynamic Harmonic Regression (DHR) and was used to interpolate and forecast tag tracks in the event data is missing. Section 2.3 provides a theoretical overview of MP, HMM, and UC models used to identify, classify, and forecast tagged marine mammal locations and movement.

### **2.1 Marine Mammal Tags**

Scientists have been using passive tracking technology to study animal migration and movement since 1803. Initially, researchers used strings, metal collars, and plastic tags to identify and recognize migratory animals (Animal Migration Tracking, 2019). Beginning in the 1960s, researchers developed devices carrying Very High Frequency (VHF) transmitters. VHF beacons were received by either stationary or handheld directional antennas and locations were manually calculated. The 1980s introduced devices carrying Passive Integrated Transponders (PITs). A PIT tag samples and stores sensor data until the tag is recovered. A decade later, satellites carrying PIT or RF receivers were used to capture, collect, and determine the precise locations of animals.

Satellite detection of marine mammal tags remains a popular tool for studying animal movement. Marine mammals are elusive and reside in extreme environments. Satellite-telemetry tags provide global coverage and deploy for many months at extreme depths and temperatures, thus making them an ideal choice for studying marine mammal movement. The Argos System, founded by NASA, NOAA, and Centre National d'Etudes Spatiales (CNES), has been providing wildlife monitoring receiver capabilities since 1978 (Why Choose Argos, 2018). In 2018, three companies (the Woods Hole Group, CLS America Inc., and Horizon Marine Inc.) merged to create the current Woods Hole Group (Stein, 2018). The Argos system is maintained by the Woods Hole Group and remains the top marine wildlife monitoring satellite service.

### 2.1.1 Argos Satellite Constellation

The Argos System is a constellation of 7 sun-synchronous polar-orbiting satellites maintained by the CNES to collect and relay meteoric and oceanographic data (The ARGOS System, 2018). A list of the 7 satellites carrying Argos Advanced Data Collection System (A-DCS) payloads are provided in Table 1. The system is in low Earth orbit (LEO) at an altitude of roughly 800 kilometers (Monitoring Weather and Climate from Space, 2018). The system receives and stores messages from Earth-based Argos Transmitters. Argos Transmitters come in three forms: moved surfaced (e.g. vessels, drifting buoys, marine animals), fixed (e.g. moored buoys and automatic weather stations), and sub-surface (marine mammals, profiling flights, gliders) platforms (CNES, 2016). Seventy ground stations are equipped to receive real-time Argos satellite messages from the estimated 22,000 Argos active transmitters scattered worldwide. Argos satellites capture any transmitters in a 5000-kilometer diameter swath of Earth and pass the poles approximately 14 times per day. Three ground stations transfer and relay Argos System messages; these stations are located at Wallops Island, VA; Fairbanks, AK; and Svalbard, Norway. There are two main processing centers: CLS America, Washington D.C.; and CLS Headquarters, Toulouse, France.

Table 1—Argos System Satellite Specifications

| Argos Satellites | Orbit | Eccentricity | Semi-major axis (km) | Perigee Altitude (km) | Apogee Altitude (km) | Inclination (deg) | Period (min) |
|------------------|-------|--------------|----------------------|-----------------------|----------------------|-------------------|--------------|
| METOP-A (MA)     | LEO   | 0.0002089    | 7198                 | 825.8                 | 828.8                | 98.5711           | 101.3        |
| METOP-B (MB)     |       | 0.0001471    | 7198                 | 825.4                 | 828.5                | 98.7003           | 101.3        |
| METOP-C (MC)     |       | N/A          | 7198                 | 825.9                 | 829.0                | 98.7              | 101.3        |
| NOAA-15 (NK)     |       | 0.00107      | 7184.62              | 804.6                 | 821.0                | 98.8              | 101.01       |
| NOAA-18 (NN)     |       | 0.0014261    | 7230.05              | 848.0                 | 869.0                | 99.17             | 101.97       |
| MPAA-19 (NP)     |       | N/A          | N/A                  | N/A                   | N/A                  | N/A               | N/A          |
| SARAL (SR)       |       | N/A          | N/A                  | 790                   | 791                  | 98.54             | 100.54       |

Argos data processing and delivering consists of 7 key steps: 1) data acquisition, 2) messages building, 3) messages delivery to satellites, 4) satellites reception of messages, 5) messages transmission back to the ground, 6) message processing, 7) and observation processing (Fig. 5). In the data acquisition stage, the transmitter's onboard sensors are capable of measuring temperature, depth, acceleration, and other activity data. Researchers choose tags based on their study objectives. With Argos-3, transmitters can be programmed to transmit only when a satellite is in view. The transmitter message includes: a preliminary synchronization sequence, a statement of message length, an identification number, sensor data or user data, and a checksum (Table 2).

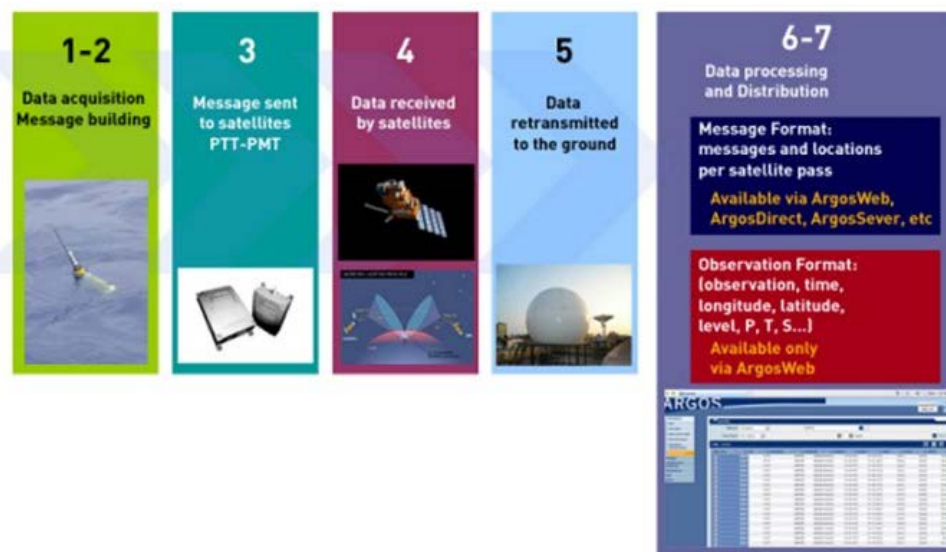


Fig. 5—Argos data processing overview

Transmission begins with Argos-certified transmitters or transceivers on each tag platform. Each tag is characterized by a unique Platform Transmitting Terminal (PTT) or Platform Messaging Transceiver (PMT) identification number. These numbers are specific to its transmission electronics and provided to the researcher after purchasing the tag. A tag transmits periodic messages characterized by the following parameters: 401.650 MHz  $\pm$  30 kHz transmission frequency, between 45 to 200 second repetition periods, and messages lasting between 360 and 930 milliseconds. Satellites equipped with Argos receiving payloads recognize a transmission by its Argos binary identification number (Table 2). Recall, a successful transmission can only occur if a satellite is in sight of the transmitter. Depending on the location of interest, there can be 2- to 4-hour blocks where there are no Argos satellites in sight. For NRL's Chesapeake Beach Detachment (CBD) located in Chesapeake Beach, Maryland, there are two time periods where satellites are not in sight over a 20-day period: 1) 0700 - 0900 UTC (0300 - 0500 EST) and 2) 1800 - 2200 UTC (1400 - 1800 EST) (Fig. 6).

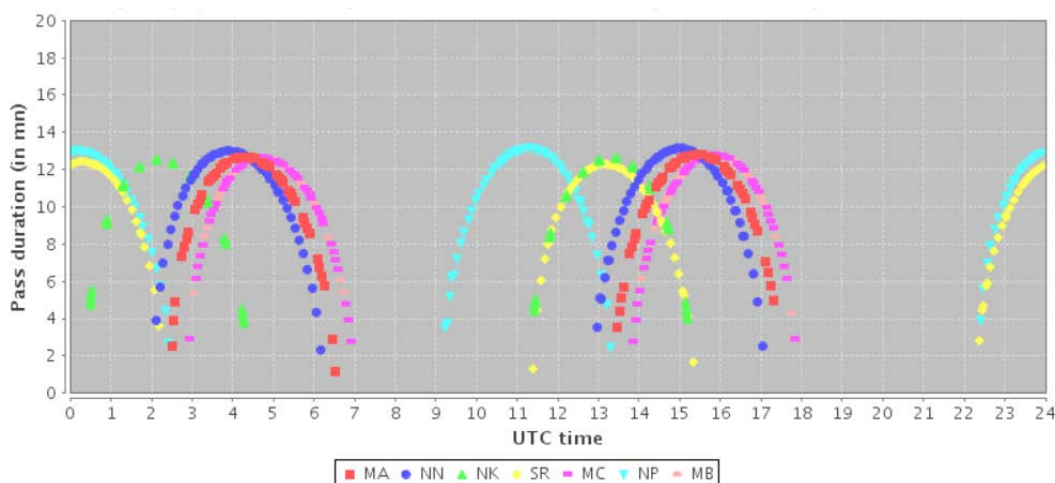


Fig. 6—Graph displays a 20-day distribution of Argos satellites' pass duration and time beginning on 16 July 2019 at NRL CBD location

Messages are either recognized immediately by message length or through the equation  $f(Ax + By + C)$ , where  $x$  and  $y$  are two encoded parts of the message. The message format contains a bit sync, frame sync, initialization number, serial number, error checking information, and sensor data (Table 2). Data is distributed in the default format, 8-bit hexadecimal words. Messages are transmitted back to ground with timestamps and measure transmission frequency. The Argos Data Collection and Location System (DCLS) data are transmitted to the ground via three different downlinks: VHF direct readout, real-time S-band, and delayed time S-band. VHF direct readout and real-time S-band downlinks are biphase/phase modulated whereas the delayed time S-band downlinks are non-return-to-zero/phase modulated.

Three evolutions of the A-DCS payload have occurred since its launch in 2006. The A-DCS system consists of receiver processing and transmit unit. The receiver processing unit has the ability to process 12 messages simultaneously (What is A-DCS, 2018). The payload evolutions, named Argos-1, Argos-2, and Argos-3, receive frequencies of 401.650 MHz and uplink data rate of 400 bits per second (bps) (CNES, 2016). Argos-3 has an additional “high” uplink data rate of 4800 bps. Bandwidth during evolutions has increased from 24kHz, 80kHz, to 110 kHz. Argos-1 and Argos-2 both transmit 500 bits of data per satellite pass and cannot downlink messages. The Argos-3 system now has downlink capabilities of 400 and 200 bps and can transmit up to 30kbits.

Table 2—Argos System Message Format

| Message Format                         | Description                      |
|----------------------------------------|----------------------------------|
| Unmodulated carrier<br>(160ms)         | Modulated carrier<br>A B C D E F |
| Minimum 360 milliseconds               | Maximum 920 milliseconds         |
| A Bit sync                             | 15 “1” bits                      |
| B Frame sync                           | 8 bits 00010111                  |
| C Initialization                       | 1 “1” bit                        |
| D Sensor number                        | 4 bits                           |
| E Identification and error<br>checking | 20 bits                          |
| F Sensor Data                          | 32 to 256 bits (by steps of 32)  |

The Argos transmitter location is then computed on the basis of the Doppler Effect measurement, requiring the transmission frequency to be stable. At the processing centers message quality is assessed, classified by platform, and distributed to the user by means of Kalman Filtering (KF) or the Least Squares Method. Both methods account for tag uplink uncertainty for smoother telemetry. Multiple tag transmission uplinks are received, measurement error is calculated, and estimated tag position is updated and sent back to the user. The difference between KF and the Least Squares Method is the KF method accounts for both measurement error and measurement states of prior positions.

Argos reports errors by categorizing each location with a Location Class (LC). An LC is classified by the type of location, estimated error, and number of messages received during satellite pass. In order from smallest to largest error, the LC classes are 3, 2, 1, 0, A, B, and Z (Table 3). Argos claims that 68% of reported locations follow the reported LC criteria. Various authors have reported that Argos locations lack precision and accuracy, claiming that LC categories are severe underestimates. Multiple studies have found LC A, categorized by Argos as having unbounded accuracy estimation, to have better

positional accuracy than LC 0 (Dubinin et al., 2010; Vincent et al., 2002; & Soutullo et al., 2007). Some warn that Argos data is not accurate enough to draw animal spatial utilization conclusions (Costa et al., 2010; Hoenner, 2012; & McKeown & Westcott, 2011). Others have tested the utility of KF and Least Squares locations empirical experimentation, concluding that the KF only improved location accuracy for LC B positions. The same authors found that less than 25% of true locations were within the LC 1, LC 2, and LC 3 stated LC error ellipse (Boyd & Brightsmith, 2013).

Table 3—Criteria for Argos Location Classes

| Class | Type  | Estimated Error        |                               | Number of messages received per satellite pass |                 |
|-------|-------|------------------------|-------------------------------|------------------------------------------------|-----------------|
|       |       | Least Squares          | Kalman Filter                 | Least Squares                                  | Kalman Filter   |
| G     | GPS   | < 100m                 |                               | 1 message or more                              |                 |
| 3     | Argos | < 250m                 |                               | 4 messages or more                             |                 |
| 2     | Argos | 250m < < 500m          |                               | 4 messages or more                             |                 |
| 1     | Argos | 500m < < 1500m         |                               | 4 messages or more                             |                 |
| 0     | Argos | > 1500m                |                               | 4 messages or more                             |                 |
| A     | Argos | No accuracy estimation | Unbounded accuracy estimation | 3 messages                                     |                 |
| B     | Argos | No accuracy estimation | Unbounded accuracy estimation | 3 messages                                     | 1 or 2 messages |

### 2.1.2 Types of Marine Mammal Tags

The wildlife tag manufacturing industry has nearly doubled since the 1990s. There exist 16 Argos equipment providers for animal tracking applications, nine of which specialize in marine animal tag manufacturing. Of the 16 providers, seven are U.S. based. A detailed list of Argos System equipment providers is provided in Appendix A.

U.S. based Wildlife Computer is the world's leading marine tag manufacturer. There exist three Wildlife Computer tags specifically designed for marine mammals: SPLASH, SPOT, and Time-Depth Recorder (TDR) tags. SPLASH tags track vertical and horizontal movements of free ranging marine life, while SPOT tags track location-only. Time-Depth Recorders (TDR) have a more extensive suite of sensors including accelerators, magnetometers, and speed sensors. TDRs are primarily used for daily diaries and short-term, fine-scale studies.

The wildly changing marine environment presents many problems for traditional GPS receivers. Maintaining signal reception can be difficult. With the exception of sunbathing pinnipeds on coastlines and docks, most marine mammals (e.g. dolphins and whales) only break the surface for a handful of seconds. GPS receivers typically have a longer time to first fix than the time it takes for a marine mammal to break the surface for a breath. In 2002, U.K. researchers developed the Fastloc® system to overcome the many problems that arise in marine GPS applications. Fastloc® is a commercially available GPS processing receiver that takes “snapshots” of the GPS signal, processes low volume satellite information, and forwards messages to the Argos system for location processing (Fig. 7). A “snapshot” can process up to ten GPS satellites and compress data in less than 12 seconds. The Fastloc® GPS system's low power

consumption attracted tag manufacturers concerned with more accurate, longer lasting tags. Today, thousands of tags are deployed with Fastloc® technology.

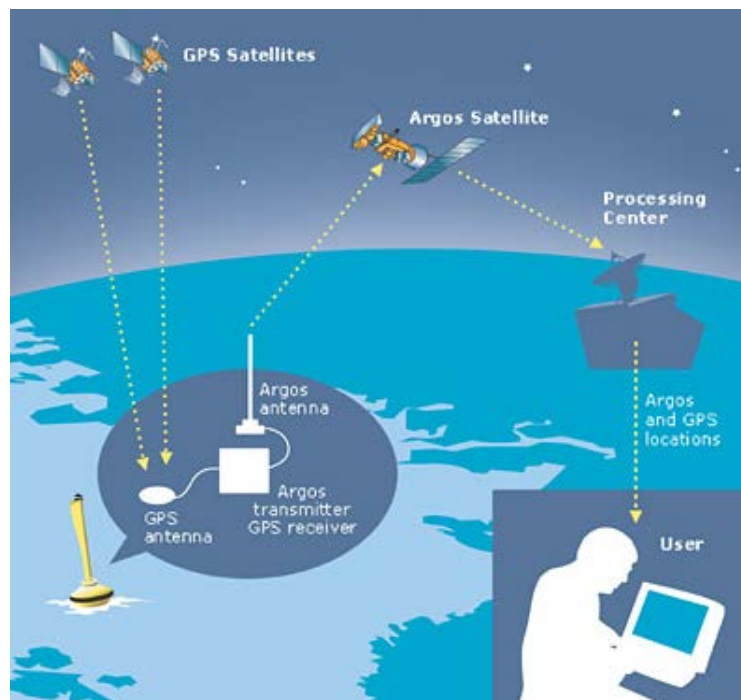


Fig. 7—Transmitting GPS data via Argos System

Some Wildlife Computer's SPLASH, SPOT, and TDR tags have Fastloc® GPS capabilities. Regardless if tags positions are calculated via Doppler Effect or Fastloc® GPS, Argos will still process positions by either KF or Least Squares Method. Because the data processing is identical for both traditional and Fastloc® GPS tags, a Fastloc® GPS tag was not used for this study. Instead, two Wildlife Computers location-only tags were used: SPOT5-303C and SPOT5-258F. According to Wildlife Computers, the SPOT tags are the most published tag type in satellite telemetry studies. The SPOT 303C tag is a humpback whale-focused tag (Appendix B). It is a rugged, transdermal tag designed to deploy for months. The SPOT 258F is smaller, designed for small whales, porpoises, and dolphins (Appendix C). It is housed in a waterproof casing with holes for dorsal fin attachment. Specifications for these tag models can be found in the Table 4. A 90 second repetition interval was chosen to preserve battery life. The default Wildlife Computers processing format uses 31 sensors (8 bits each,) and decimal processing (Table 4). Hexadecimal values are provided to the user upon purchase; however, they are primarily used by the manufacturer to program the tag.

The Wildlife Computer TagAgent software is used to communicate via USB with tags when installed on a compatible computer. Within the TagAgent software, tag battery and sensor health data are displayed. Test transmissions can be sent via the TagAgent as long as the tag is plugged into a PC through its USB port. Tags are activated either through the TagAgent software or through a magnetic switch on the tag. LED lights indicate whether the tag is in START mode or STOP mode. Prior to deployment, tag ports should be sealed with a provided silicon applicator and placed in START mode, transmitting at their programed repetition rate.

For marine species, tag transmissions can only occur when the marine mammal breaches the surface and the antenna is within visibility of the Argos constellation. A wet/dry sensor on the tag gauges when the antenna has breached the surface. When the wet/dry sensor is in the “wet” state, the tag is in battery preserve mode and will not transmit. When the tag is in a dry state, the tag will attempt to transmit a message. Therefore, successful message transmission is dependent on the wet/dry sensor activation, the programmed repetition rate, and satellite visibility.

Table 4—Marine Mammal Satellite Telemetry Tag Specifications

| Characteristics                                            | SPOT5-258C                           | SPOT5-303F |
|------------------------------------------------------------|--------------------------------------|------------|
| Platform Transmitting Terminal (PTT) Identification Number | 174292                               | 183394     |
| Number of Sensors                                          | 31                                   |            |
| Sensor Format                                              | 8bits/sensor with decimal processing |            |
| Uplink Frequency (UHF band)                                | 401.65 MHz                           |            |
| Message Length                                             | Up to 32 bytes                       |            |
| Power                                                      | Battery                              |            |
| Transmission Time                                          | 360-920ms                            |            |
| Repetition Period                                          | 90                                   | 45         |
| Hexadecimal                                                | 3141E4C                              | 7B3C326    |

### 2.1.3 Archived Marine Mammal Data

Marine mammal telemetry data can be accessed in three ways: 1) collecting data from a deployed satellite telemetry tag, 2) requesting archived or active tag data from other researchers, or 3) downloading tag data from a marine mammal data repository site. Marine mammal repositories were developed to encourage collaboration and community among researchers. The U.S. Animal Telemetry Network (ATN) and Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP) provide a wide range of datasets and contributors (National Ocean Council, 2016 & Marine Geospatial Ecology Lab, 2019).

OBIS-SEAMAP is hosted at Duke University’s Marine Geospatial Ecology Lab, Nicholas School of the Environment. The site contains thousands of marine life points of observations, acoustic and satellite telemetry tracks, vessel and aircraft survey effort lines, citations, and metadata about the research. Data formats include comma separated variable (csv), shape files (shp), keyhole markup language (kml), or JavaScript object notation (JSON). Users may sort by dataset type, contributor type or species type. As of June 2019, there are 1,145 datasets of 717 species amounting to a total of 5,996,930 records (Marine Geospatial Ecology Lab, 2019). OBIS-SEAMAP is an excellent archive for marine mammal abundance, occurrence, and distribution model development. However, OBIS-SEAMAP lacks real and near-real time marine mammal, which is a service ATN aims to provide.

ATN is a multi-agency program hosted within the U.S. Integrated Ocean Observing System (IOOS) Program Office at NOAA. The site has a web-based, map interface where users can visualize

animal telemetry acoustic and satellite tagging efforts worldwide (Animal Telemetry Network, 2018). The contributors of datasets come from both academia and federal entities. Datasets are assembled at the Data Assembly Center operated by Axiom Data Science. In summer 2019, ATN will enter Phase 3 of a four-stage data transition project. Phase 3 will curate original telemetry datasets in a logical and efficient structure and secure datasets on an operational environment called ATN Research Workspace. As of June 2019, ATN Research Workspace is in limited-access mode and data cannot be immediately accessed. In the interim, each dataset displayed on ATN's map interface has an associated project description and point of contact for data requests.

## 2.2 Satellite Telemetry Tag Collection Methods

If marine mammal data is integrated in MDA systems, the system should generate marine mammal proximity alerts for vessel operators. An example alert may be: *"Caution, humpback whales ahead. Adjust course to maintain at least 5 miles standoff from sighted whales and maintain speed below 8 kts until at least 10 miles from sighted whales. Do not radiate high power sonar until at least 20 miles from last sighting."* Informative alerts such as this cannot be generated if marine mammal data is unreliable. There are various ways to access and collect marine mammal telemetry data; this section describes the most common collection methods used by researchers. The two most common data retrieval methods are to 1) subscribe and download directly from the user data portal, Argos Web or 2) purchase a CLS America Goniometer (radio direction finder). These methods are described in detail in Sections 2.2.1 and 2.2.2.

There are thousands of active marine mammal telemetry devices whose transmissions may be intercepted and geolocated. If a marine mammal tag transmission identification capability existed within U.S. Navy signal intelligence (SIGINT) systems, marine mammal locations would be provided in near real time. A marine mammal tag identification method using free SDR software is explored for an alternative tag detection approach. Section 2.2.3 explores the signal characteristics of marine mammal telemetry tag transmissions using an inexpensive, commercial SDR; *Hack RF One* by Great Scott Gadgets; and open-source GNU Radio software.

### 2.2.1 Argos Web Data

When a user purchases a satellite telemetry tag with an Argos transmitter, the user is issued a PTT ID for each tag. This number is encoded in the tag message transmissions for message recognition purposes. Argos charges €15 (\$19.06) per active PTT ID and a €4 (\$5.08) daily fee. Users then elect how their data should be delivered. Data is delivered automatically via a File Transfer Protocol (FTP), delivered by email for €30 per month (\$38.12), or is accessed freely on a data portal website (Argos Web). The Argos Web is maintained by CLS and CLS America. Once a data delivery method is elected, the user selects whether their data is processed via the KF or the Least Squares Method. The KF was first used by the Argos processing centers in March 2011 (CNES, 2016). Argos claims that the KF significantly increased positional accuracy and now recommends users to select this technique.

For this study, the KF was chosen for SPOT 303C and SPOT 258F telemetry data and freely accessed on Argos Web. Users may access data up to ten days on Argos Web. Users must issue an archive data request to access data older than ten days. Telemetry data may be exported to CSV, Excel, HTML, KML, or PDF files. Raw and filtered files containing the animal tag positions are provided. The raw data file provides information regarding the satellite pass data and time, the satellite identification number, duration, error ellipse properties, power, tag PTT/PMT ID and geolocation of the tag.

### 2.2.2 CLS RXG-134/Goniometer

CLS's radio direction finder, RXG-134, contains a powerful receiver tuned to the Argos frequency band capable of locating the transmitter, providing distance and direction, and demodulating messages. The RXG-134 is a handheld device that comes equipped with two antennas for direction finding: the Goniometer and Bayonet Neill-Concelman (BNC) antenna. The Goniometer's range is roughly 100 kilometers and is embedded with GPS to provide receiver locations. CLS claims the RXG-134 and Goniometer configurations receive directions of arrivals at  $\pm 5$ -degree accuracy and  $\pm 1$ -degree resolution (Table 4). The RXG-134 receiver, Goniometer antenna and its 5-meter cables, BNC antenna, USB cable, main power converter, and antenna mounts amount to \$10,000 (Argos Goniometer, 2018). Researchers have the option of renting the direction-finding system from CLS because it is typically used for tag recovery in the field.

Table 4—CLS Goniometer Technical Characteristics

| Characteristics                            | Specifications                                                                   |
|--------------------------------------------|----------------------------------------------------------------------------------|
| Frequency Range                            | 401.620 – 401. 680 MHz                                                           |
| Bandwidth                                  | $\pm 30$ kHz to 0.5 db                                                           |
| Frequency Stability                        | $\pm 3.5$ ppm over the temperature range                                         |
| Minimum detection sensitivity              | -131 dbm                                                                         |
| Accuracy of angle measurement              | $\pm 5$ degrees                                                                  |
| Resolution of the measurement of the angle | $\pm 1$ degree                                                                   |
| Battery Charging Time                      | 7hr (external), 15hr (USB)                                                       |
| Internal Battery Capacity                  | 6800 mAh                                                                         |
| Temperature Range                          | 0 deg. C to + 45 deg. C while charging<br>-20 deg. C to + 50 deg. C while in use |

Timestamped, received tag transmissions are stored internally on RXG-134 and can be viewed on a PC once the RXG-134 software is installed. Researchers collect tag transmissions, plug the RXG-134 device into the PC, and save data they wish to export as "Favorite Platforms." If received transmissions are not saved as a "Favorite Platform," the RXG-134 will erase data from its internal memory. In an initial investigation, test transmissions from the SPOT 303C and SPOT 258F were collected by the RXG-134 Goniometer system for approximately 20 minutes. Two hexadecimal IDs appeared on the RXG-134 screen corresponding to each tag: 7B3C326 for the SPOT 303C and 3141E4C for the SPOT 258F tag. Along with 7B3C326 and 3141E4C, four other hexadecimal IDs appeared on RXG 134's "Receiving Platforms" screen. Given there were no other tags in range, it was clear the receiver incorrectly decoded the tag's transmitted message. Because the four other hexadecimal IDs were not listed as favorite upon exported the data from the receiver, they were erased and only 7B3C326 and 3141E4C remained. The RXG-134 hexadecimal ID decoding has faults; therefore, it is critical to ensure that all received IDs are saved as "Favorite Platforms" for data to be saved. Once received data is dubbed "favorite," the user is able to export a text file containing the following values:

- Date
- Frequency of tag platform (Hz)
- Instantaneous direction relative to the antenna (deg.)

- Mean direction relative to the antenna (deg.)
- Signal level received from tag (dBm)
- Transmission period (secs)
- Latitude of antenna (deg.)
- Longitude of antenna (deg.)
- Direction towards the tag relative to the north (deg.)
- Length of data (bytes)
- Data content (message)

Decoded latitude and longitude in the case a tag is equipped with a Fastloc® GPS (deg.).

CLS claims the tag message is decoded and stored in “Data content.” This is a misleading claim, considering only tags whose decoding scheme is programmed into the RXG-134 can be decoded. After inquiry, it was discovered that Wildlife Computers does not provide their decoding scheme.

The most useful information provided by the RXG-134 receiver is the calculated azimuthal angle from receiver to tag. These azimuth angles can be used to triangulate the tag’s approximately location. In the 20 minute initial investigation previously described, an accuracy test was completed for the goniometer positions. The Ashtech® Global Navigation Surveillance System (GNSS) receiver is a Differential GPS (DGPS) and is used for ground truth positioning for the SPOT 303 C and SPOT 258F. Each tag was placed upright, on top of the DGPS receiver. GPS positions provided by the DGPS receiver fell within the 10 mm horizontal and 20 mm vertical accuracy range provided by the manufacturer. The RXG-134 Goniometer systems were walked in a clockwise direction at approximately 90 feet (27.432 meters) from the stationary DGPS and tags for 20 minutes (Fig. 8).

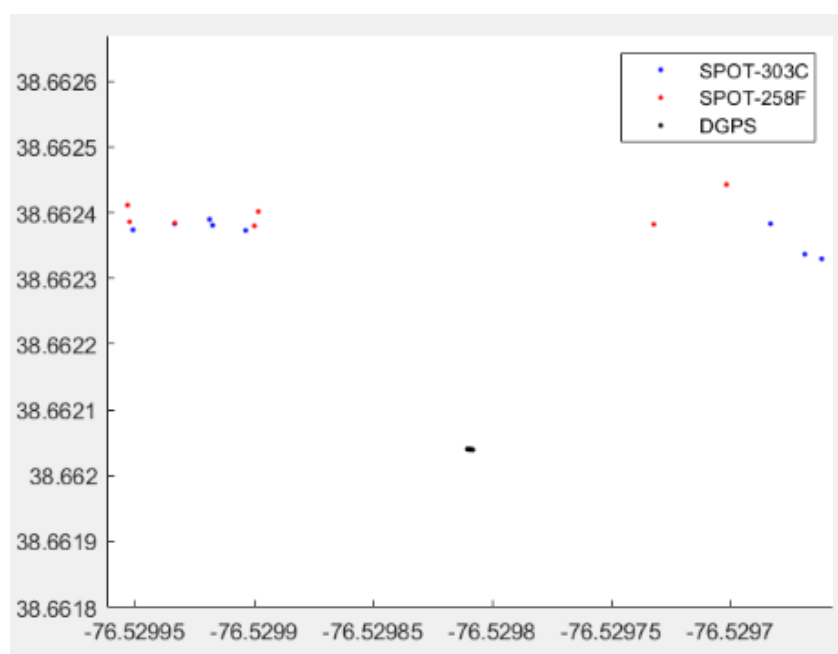


Fig. 8—Triangulated locations of Wildlife Computers marine mammal tags SPOT 303C (blue circles) and SPOT 258F (red circles). X-axis represents longitude and y-axis represents latitude. Actual positions of tags and DGPS receiver are condensed black circles, accurate to 10 mm horizontally, and 20 mm vertically.

RXG-134 Goniometer system received azimuth angles that were used to approximate positions of tags. Data was exported using the RXG-134 software and processed in MATLAB. Pierlot and Van Droogenbroeck’s “*ToTal*” triangulation algorithm was used to approximate positions of tags (Pierlot & Van Droogenbroeck 2014). The algorithm requires three direction measurements and positions; therefore, for every three received tag directions, a position could be calculated (Fig. 9). The “*ToTal*” algorithm was chosen because of its superior accuracy to other algorithms, such as Ligas and Font-Llagunes (Pierlot & Van Droogenbroeck, 2014). In a 20 minute period with a 90 second repetition rate for each tag, approximately 13 transmissions should be emitted per tag. The RXG-134 only received nine transmissions for each tag (represented as hexadecimal IDs 7B3C326 and 3141E4C on the RXG-134 “Receiving Platforms” screen). Recall that four other hexadecimal IDs appeared during this experiment, which could account for the missing transmissions; however it was unclear which hexadecimal ID corresponded to which tag. Using ‘*ToTal*’ and nine positions per tag, seven estimated positions were calculated for each tag. The longitude and latitude error between tag position estimates and true DGPS position was 31.79 and 39.72 meters respectively. This error is suspected to stem from the azimuth angle accuracy. This error may not be considerable in the context of locating a 15-meter tagged humpback in the field. This error *does* impact predicting fine-scale movements of marine mammals, which is addressed in the following sections.

---

**Algorithm 1** Final version of the ToTal algorithm.

---

Given the three beacon coordinates  $\{x_1, y_1\}$ ,  $\{x_2, y_2\}$ ,  $\{x_3, y_3\}$ , and the three angles  $\phi_1, \phi_2, \phi_3$ :

- 1) compute the modified beacon coordinates:

$$\begin{aligned} x'_1 &= x_1 - x_2, & y'_1 &= y_1 - y_2, \\ x'_3 &= x_3 - x_2, & y'_3 &= y_3 - y_2, \end{aligned}$$

- 2) compute the three  $\cot(\cdot)$ :

$$\begin{aligned} T_{12} &= \cot(\phi_2 - \phi_1), & T_{23} &= \cot(\phi_3 - \phi_2), \\ T_{31} &= \frac{1 - T_{12}T_{23}}{T_{12} + T_{23}}, \end{aligned}$$

- 3) compute the modified circle center coordinates:

$$\begin{aligned} x'_{12} &= x'_1 + T_{12}y'_1, & y'_{12} &= y'_1 - T_{12}x'_1, \\ x'_{23} &= x'_3 - T_{23}y'_3, & y'_{23} &= y'_3 + T_{23}x'_3, \\ x'_{31} &= (x'_3 + x'_1) + T_{31}(y'_3 - y'_1), \\ y'_{31} &= (y'_3 + y'_1) - T_{31}(x'_3 - x'_1), \end{aligned}$$

- 4) compute  $k'_{31}$ :

$$k'_{31} = x'_1x'_3 + y'_1y'_3 + T_{31}(x'_1y'_3 - x'_3y'_1),$$

- 5) compute  $D$  (if  $D = 0$ , return with an error):

$$D = (x'_{12} - x'_{23})(y'_{23} - y'_{31}) - (y'_{12} - y'_{23})(x'_{23} - x'_{31}),$$

- 6) compute the robot position  $\{x_R, y_R\}$  and return:

$$x_R = x_2 + \frac{k'_{31}(y'_{12} - y'_{23})}{D}, \quad y_R = y_2 + \frac{k'_{31}(x'_{23} - x'_{12})}{D}.$$


---

Fig. 9—“*ToTal*” triangulation algorithm adapted from Pierlot & Van Droogenbroeck (2014)

### 2.2.3 Software Defined Radios (SDR) for Marine Mammal Tag Detection

A well-known activity among amateur radio enthusiasts is “transmitter hunting,” also known as “fox hunting.” During a transmitter hunt, participants use DF techniques to determine the direction of a transmitter. Once several direction readings are collected, the participants will triangulate the transmitter’s location (Transmitter hunting, 2018). Transmitters can either be mobile or installed at a fixed location. Participants typically use directional antennas or radio direction finders during a hunt. Older directional antennas rotate to collect multiple direction readings. A more popular directional antenna is a quad antenna, which collects reads from each element. Antennas are tuned to the transmitter frequency by SDRs. SDR are radio communication systems translated into software. SDRs are programmed on a personal computer to receive, transmit, amplify, modulate, demodulate, detect, or convert any signal of interest. Various software packages are capable of programming SDRs. There are 13 different software packages available for amateur radio enthusiasts; this report uses GNU Radio because it implements a user-

friendly, flow-diagram framework (Software-defined Radios, 2019). GNU Radio’s infrastructure is written in both C++ and Python allowing smooth, flexible, and compatible integration for other applications.

This work employs techniques in recreational transmitter hunting to receive, detect, and collect satellite telemetry tag transmissions deployed on marine mammals. A HackRF SDR by Great Scott Gadgets was connected to a Diamond D220 Mini Discone Wideband Scanner receiving antenna via its SMA female antenna port. The antenna port power is 50 mA at 3.3V. The Diamond D220 antenna has 100 to 1600 MHz receiving frequency, 50 Ohm impedance, and max power of 50 Watts. The SDR was also connected via USB to a computer with GNU Radio software installed. The computer had an Intel Xeon W-2133 CPU at 3.60GHz with 32.0 GB of RAM. The HackRF SDR has a 1 MHz to 6 GHz operating frequency capable of sampling up to 20 million samples per second (Great Scott Gadgets, 2016). Samples from SDR are 8-bit quadrature.

The National Computing Centre (NCC) group provides a “RF Testing Methodology” tutorial to demonstrate the ease of capturing, identifying, transforming, and demodulating signals in GNU Radio (NCC Group, 2019). The tutorial requires installation of GNU Radio, a free signal processing software development toolkit; Baudline, a time-frequency analysis tool designed for scientific visualization; and RF hardware. The RF hardware used in this application consists of a software-defined radio, Great Scott Gadget’s HackRF, and a receiving antenna.

Each tag is set to “Start” mode, transmitting at a center frequency of  $401.650 \text{ MHz} \pm 30 \text{ kHz}$  every 90 seconds. Each tag has a whip antenna emitting a maximum average power of 800 mW. The tag antenna is vertically aligned and is roughly three feet away from the receiving antenna during transmissions in order to capture a clear, strong tag transmissions. The HackRF initiates in the “osmocom Source” block (Fig. 10). The center frequency for the HackRF is set to 401 MHz with a sample rate at least twice the maximum frequency. The higher the sample rate, the clearer the signal will be, thus a sample rate of 4 million (the HackRF is simultaneously sampling 4 million signals every second). The “DC Blocker” block filters the direct current from the power supply to the HackRF. If the “DC Blocker” is not used, there will be peak in the center of the flow graph.

The “QT GUI Sink” produces a 1024-sized Fast Fourier Transform (FFT) window in Fig. 10. Note that a sample rate of 4 million in the time domain translates to a  $\pm 4 \text{ MHz}$  window in frequency domain. In the FFT plot, we see the tag transmission peaked at 401.65 MHz and as expected (Fig. 11). All other peaks are aliases of the tag transmission. To address this, the signal of interest is centered and anti-aliasing filters are applied.

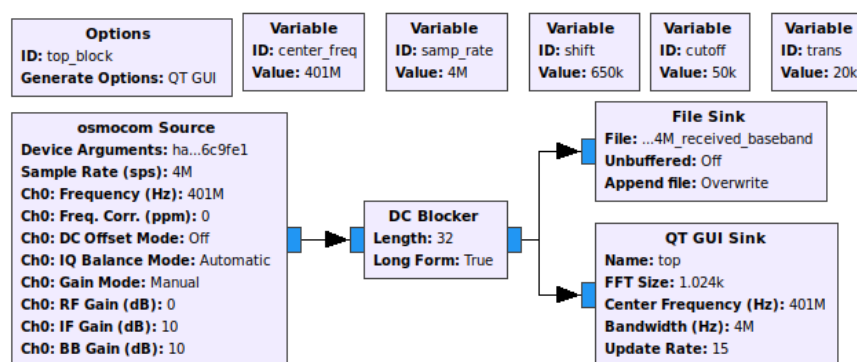


Fig. 10—GNU Radio flow graph used to receive animal tag transmissions. The ‘osmocom Source’ block configures the RF hardware used to capture the signal (a HackRF and Diamond D220R Antenna (100-1600 MHz)).

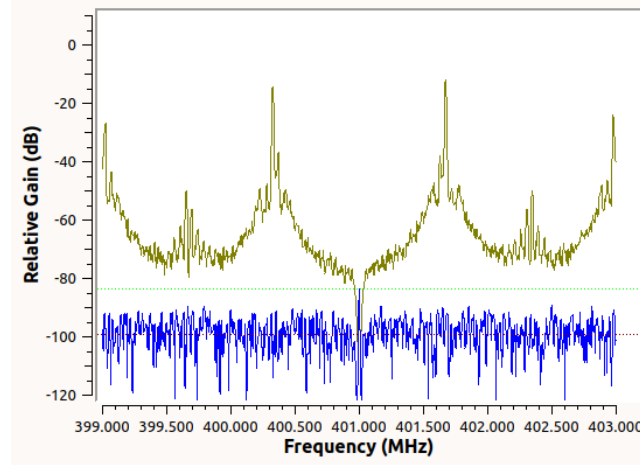


Fig. 11—A 1024-sized FFT plot in GNURadio when the “QT GUI Sink” block is executed. Green lines depict peak hold produces by the SPOT 303C GPS tag transmission and blue lines depict received frequencies at the time the plot was captured. The tag transmission occurs at 404.65 MHz (green) and all other green peaks are aliases.

The received baseband signal is split into 50 Mb files to avoid overloading the CPU. Only a file containing the full signal is saved for filtering. This file is called upon by the “File Source” block (Fig. 12). The “Throttle” block is another mechanism to ensure that the CPU is not overwhelmed. Note that the tag transmission occurred 650 kHz above center frequency. When a cosine waveform at 650 kHz is multiplied with the 50 Mb file containing the tag transmission, the tag transmission is then centered.

The centered signal is then sent through a low pass filter with a maximum frequency set to 50 kHz and a bandwidth of 20 kHz. The 50 kHz and 20 kHz values were found empirically using both tags and are named the “Cutoff Frequency” and “Transition Width,” respectively. The “Quadrature Demod” block then transforms the complex data type output from the low pass filter to a float data type (Fig. 12). Converting filtered tag signal transmissions to float data types allows another low pass filter to be applied. The second “Low Pass Filter” block in Fig. 12 uses the Argos baud rate of 24 kHz as the “Cutoff Frequency” and half of the baud rate, 12 kHz, as the “Transition Width.” Starting with a 4 million sample rate and considering 24 kHz baud rate, samples per bit becomes 1666. Samples per bit is delineated by a factor of 100; because there is no need to represent thousands of samples per bit, 16 samples per bit is enough.

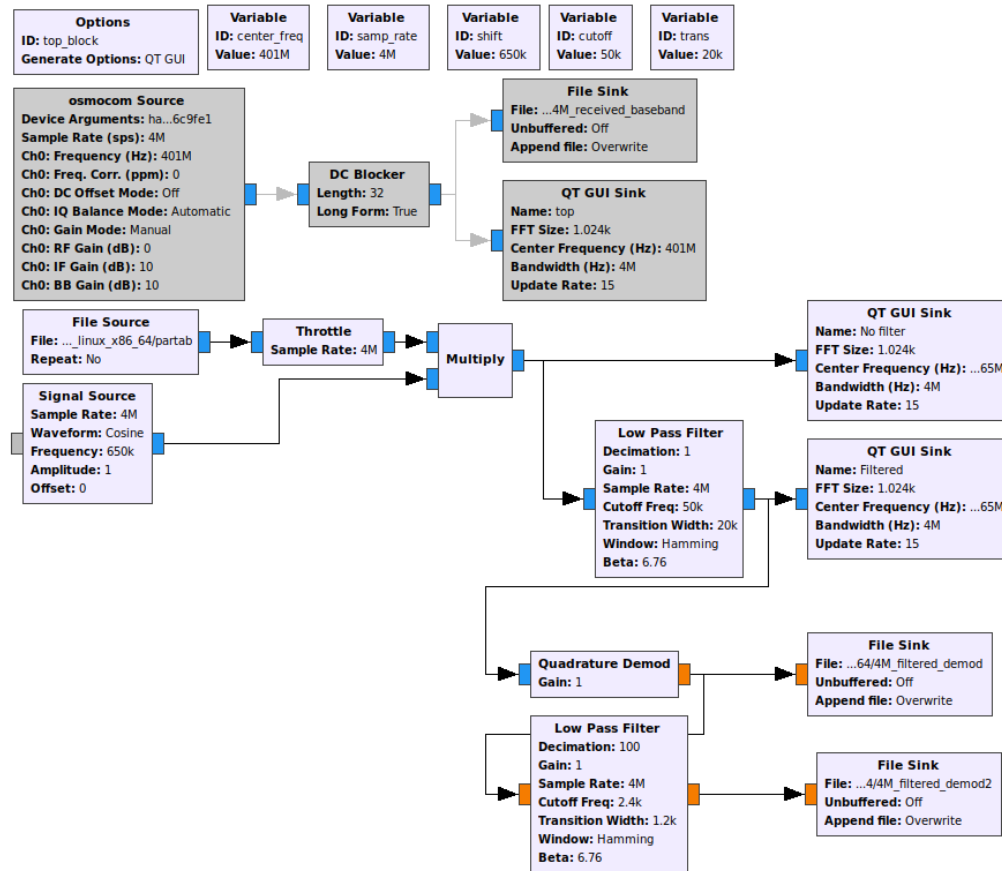


Fig. 12—GNURadio flow graph leveraging a HackRF SDR and Diamond Antenna D220R to capture two animal tag models from Wildlife Computers. Gray boxes receive tag signals at baseband and save data to a local file. Gray boxes are disabled when light blue boxes read, filtered, and reformat received tag signal data.

The spectrograms are analyzed in a digital spectrum analyzer, Baudline, and are used to confirm that 16 samples per bit is more than enough information. In Figs. 13 and 14, the 82–160 milliseconds carrier and 56–68 bit message preamble are clear before the rest of the data are introduced. The Wildlife Computer SPOT 303C tag contains more onboard functionalities and therefore has a more data to transmit than the older Wildlife Computer SPOT 258F tag model. In Baudline, tag signals are exported as Waveform Audio File Format (WAV) files. The WAV files containing messages from the SPOT 303C and SPOT 258F tags were loaded and read into MATLAB using the file “audioread.m.” Data from each of the wave files were stored into one-dimensional arrays and z-normalized. The two collects from Baudline have been concatenated to demonstrate the different message lengths produced by the tag transmission (Figs. 13 and 14). From the tag specification sheet, message length for the SPOT 303C is 64 bytes, and the SPOT 258F message length is half that. Figs. 13, 14, and 15 display these values.

This section demonstrates how to create simple GNU radio flow graphs based on a transmitter’s technical specification sheet. The GNU radio flow graph format is intuitive and flexible. Each block’s parameters can be adjusted and reoriented based on the receiving task. GNU radio is Python based, and therefore users have the freedom to create custom blocks from Python scripts. Time-series’ containing signals of interest can be received, played back, and stored using equipment costing less than \$1,000. Data collected in GNU Radio may be transformed into a Matrix Profile (MP) for detection of motifs and anomalies (Section 2.3.3 and 3.1).

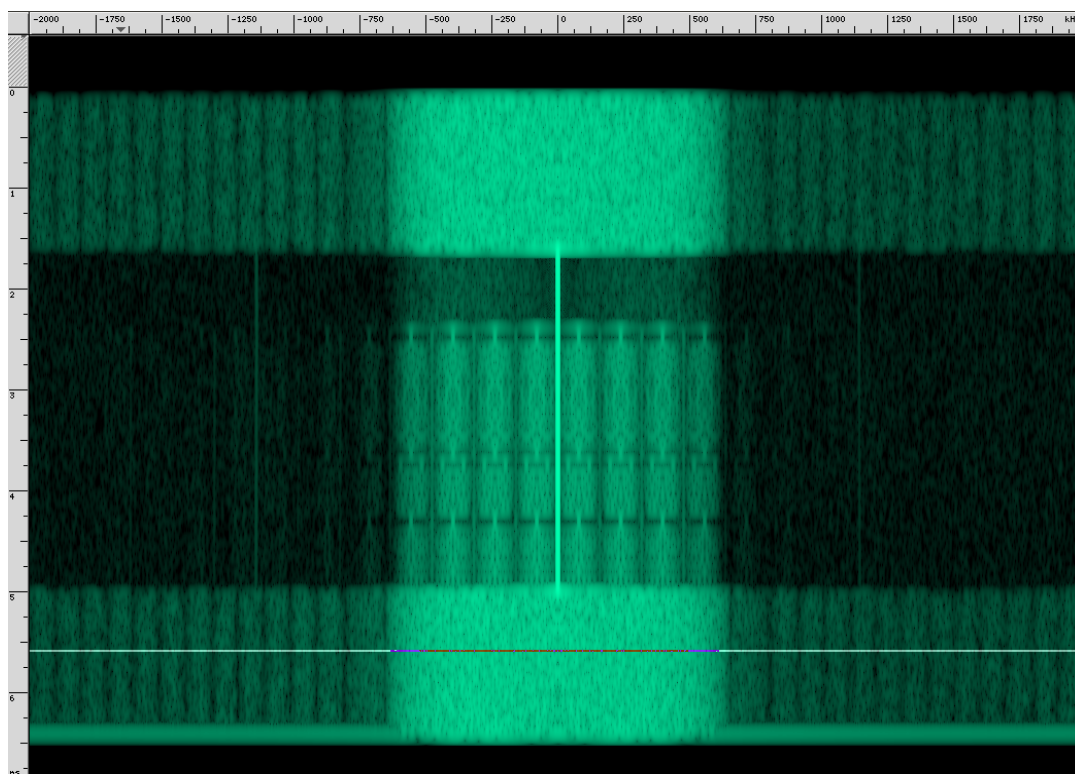


Fig. 13—Spectrogram of the SPOT 303C animal tag produced from GNU Radio flow graph and viewed in *Baudline*.  
The y-axis is time in milliseconds and the x-axis is frequency in kHz.

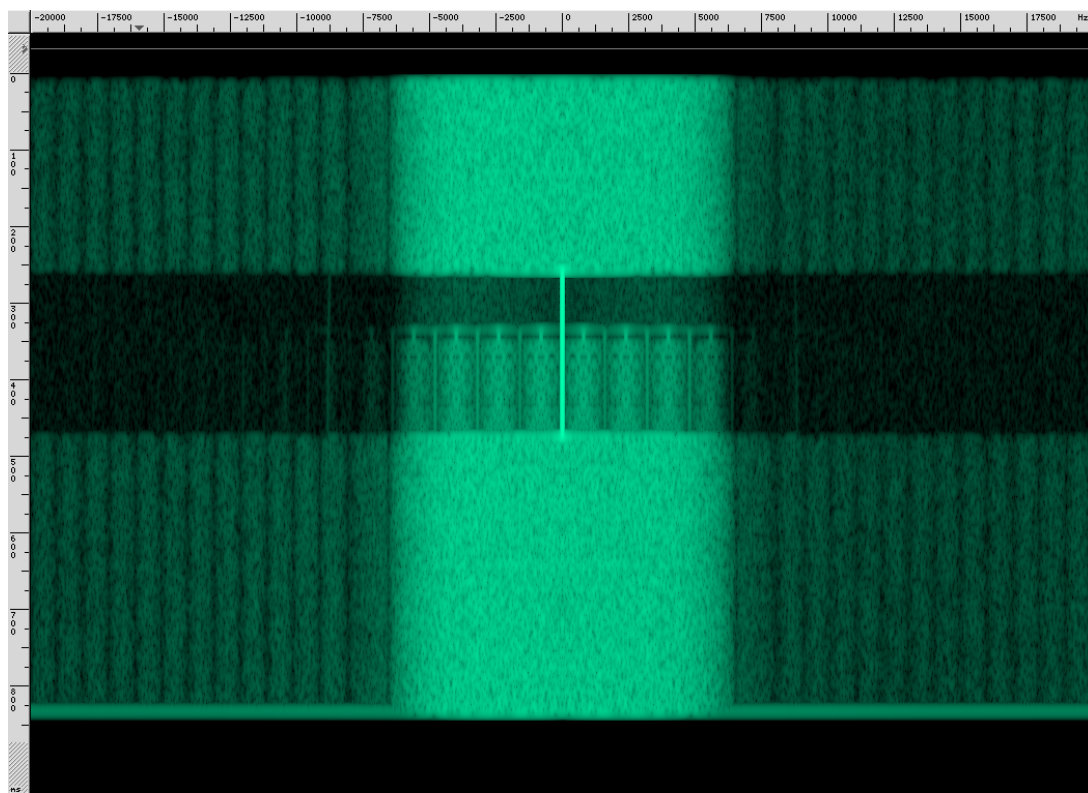


Fig. 14—Spectrogram of the SPOT 258F animal tag produced from GNU Radio flow graph and viewed in *Baudline*.  
The y-axis is time in milliseconds and the x-axis is frequency in kHz.

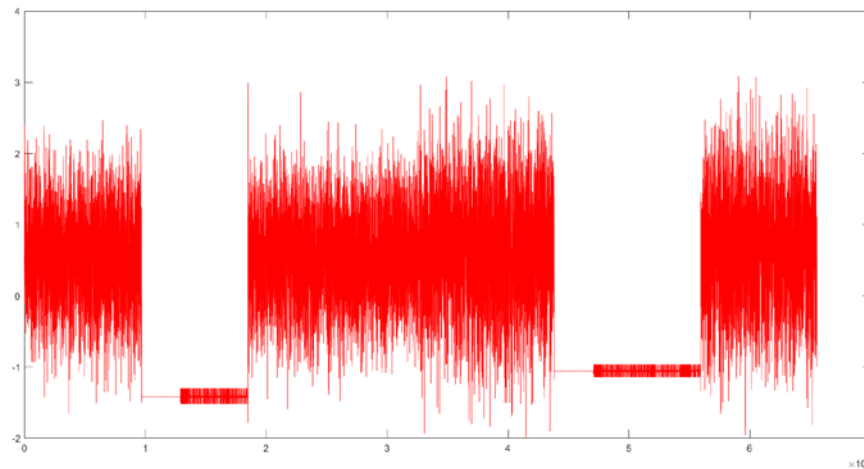


Fig. 15—MATLAB concatenated time series plot of the SPOT 258F and SPOT 303C wave files generated from *Baudline*

## 2.3 Theoretical Foundations for Modeling Marine Mammal Movement

Recall the fictional marine mammal from Section 2.2: *“Caution, humpback whales ahead. Adjust course to maintain at least 5 miles standoff from sighted whales and maintain speed below 8 kts until at least 10 miles from sighted whales. Do not radiate high power sonar until at least 20 miles from last sighting.”* This alert is detailed and contains many decision-making elements. Historical knowledge of species, current behavioral state, time of year, geography, and weather conditions are some of the many factors that contribute to how vessels should maneuver around a marine mammal. The following sections explore techniques for determining marine mammal behavior and future positions. In Section 2.3.1, Hidden Markov Models (HMM) are used to determine behavioral “states” among marine mammal time series data. In Section 2.3.2, a derivation of the stochastic SS model, the UC model for marine mammal time series is provided. The UC model assumes harmonic trends in the observed data, smooths, interpolates missing values and forecasts data to the users desired time step. The HMM and the UC model are intuitive models that should be used to generate marine mammal alerts in MDA systems.

### 2.3.1 Hidden Markov Models (HMM) for Marine Mammal Movement

The Hidden Markov Model (HMM) is a discrete time model that assumes there is an underlying, unobserved process,  $\{C_t: t = 1, 2, \dots\}$  among observations  $\{X_t: t = 1, 2, \dots\}$  (Fig. 16). The unobserved process,  $C_t$ , consists of  $m$  states where the probability,  $p_t(x)$  of being in state,  $m_t$ , depends on the prior state,  $m_{t-1}$ , such that  $p_i(x) = P(X_t = x | C_t = i)$ . An observation is a measured statistic, such as step size and turning angle between two samples.

The HMM may include covariates assumed to generate perturbations in the observations. Covariates could have seasonal, cyclical, linear, or nonlinear effects on the observations. Covariates, such as oceanographic phenomena, drive the unobserved process,  $C_t$  to transition between states. For example, consider the covariate, ‘sea state’ and its effect on bioluminescence marine organisms. As the sea state becomes more volatile, the bioluminescence organisms will become disturb and illuminate. The bioluminescence organism went from a no illumination state to an illumination state. In this example, there are 2 states. States are classification markers that depend on the system of interest. There are many definitions of state, including, but not limited to, temperature, size, activity level, and behavior.

A 3-state HMM produces  $p_1(x)$ ,  $p_2(x)$ , and  $p_3(x)$  state-dependent probability distributions, and therefore 6-state transitions between states (Patterson et al., 2017). Conditions that initialize the model include observations extracted from the multivariate time-series data, state-dependent distribution parameters, and potential state-switching covariates,  $Y_i$  (Fig. 16). Unlike the bioluminescence example, most systems ‘states’ are not directly observed. Most systems generate a series of measurements over time, and from those measurements observations can be made. If position over time is the system, an example of  $X_t$  is step size and turning angles calculated directly from the positions. The HMM requires the probability distributions of  $X_t$ , step size, and turning angles to be known. In this paper, step sizes are assumed gamma distribution and turning angles are assumed to be von Mises distribution. A gamma distribution has parameters  $k_i$  and  $\theta_i$  while a von Mises distribution has parameters  $\mu_i$  and  $\kappa_i$ . The HMM is initiated under some set of initial parameters and a state likelihood sequence,  $L_{\theta}$ , for observations  $X_1, X_2 \dots X_t$  is calculated. The likelihood function,  $L_{\theta}$ , is then fitted by the expectation maximization algorithm in order find maximum-likelihood estimates for the parameters. These process iterates until a global optimum for all parameters is met. Poorly chosen initial parameters result in the algorithm that is unable to find a maximum likelihood estimate (Michelot, Langrock, & Patterson, 2016). In order to prevent this, initial parameters must be representative of model.

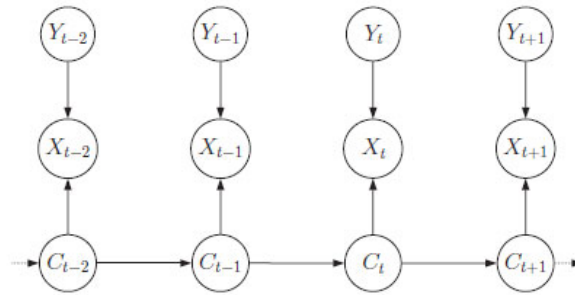


Fig. 16—Directed graph of HMM including state-switching covariates adapted from Zucchini, MacDonald, and Langrock, 2009

HMMs are appropriate for data collected at regular or meaningful time intervals (e.g. each time a marine mammal surfaces and a satellite tag is able to transmit). The underlying state sequence reported by HMMs has been interpreted as animal movement behavioral states. Elk, sharks, blue whales, birds, and fruit flies are just some species whose movement behavior has been analyzed using HMMs (Morales, 2004; Franke et al., 2004; Mckeller et al., 2015; van de Kerk et al., 2015; and Towner et al., 2016). In tagged elk tracks, the HMM reported two behavioral states defined by: a less active state of small step sizes and uniform turning angles, and an active state of large step sizes and directed turning angles (the animal follows a straight, directed path) (Morales, 2004). It should be emphasized that “states” are proxies for the animal’s actual behavioral state and should be interpreted cautiously (Patterson et al., 2017).

It is intuitive to think of animals’ tracks as different correlated, biased, and biased correlated random walks; it is useful to think of each state in an HMM as a distinct random walk (Zucchini et al., 2009). If an animal’s track begins as a random walk (scattered) and then transitions to a biased correlated random walk (has more direction), it can be assumed that some underlying force generated this change in random walk. In marine mammal tag data, there can be periods of random, dense locations near shore and locations dispersed over many miles from shore as if some polarizing force dispersed the locations. A polarizing behavior was found in blue whale dive data and covariates were considered in order to understand what drove this behavior. It was found blue whales were less likely to initiate deep diving foraging behavior in the presence of high frequency sound exposure (DeRuiter et al., 2016).

R-based HMM software has been developed by a research group, EcoHMM. The EcoHMM group members actively work on ecological applications of HMMs and maintain the R-based “moveHMM,” repository (Leos-Barajas & Langrock, 2019). The software, “moveHMM,” is available in the programming language R’s package repository, Comprehensive R Archive Network (CRAN). The “moveHMM” repository is accessible, intuitive, and flexible to the needs of many research problems. This paper explores HMM track behavior encoding for time series involving marine mammal tag data. Multistate HMM models are described in Section 4.2.

### 2.3.2 Stochastic Models for Forecasting Marine Mammal Movement

Considering radio telemetry is inherently noisy and dependent on time at surface, behavior, and satellite pass conditions, stochastic SS models are ideal for evaluating telemetry data. UC models are a particular type of SS framework used to evaluate and forecast time series data. Kalman filters are exploited within these frameworks to estimate Time Varying Parameters (TVP). In this application, step size and turning angle TVPs are estimated using a Dynamic Harmonic Regression (DHR) model within the CAPTAIN Toolbox for MATLAB (Taylor, Pedregal, & Young, 2017). This model highlights the proficiency of UC models for smoothing, decimating, identifying trends, and forecasting marine mammal behavior from marine mammal telemetry data. Seasonal and cyclical trends in nonlinear data are observed in many nonlinear datasets, such as business cycles affecting stock market prices, diurnal cycles driving feeding behavior in wild animals, social media engagement during peak hours, the moon’s influence on tidal forces, etc. Many of these phenomena can be explained physically or have been observed over many years.

A multitude of interacting systems dictate the movement of a marine animal. Examples seen in the field include diurnal diving cycles, seasonal migratory trends due to sea surface temperatures, increasing underwater soundscapes affecting echolocation, and biological compasses within species (Campbell et al., 2015; Gulesserian et al., 2011; & Tsujii et al., 2018). Marine mammal telemetry data is nonstationary; marine mammal position changes over time at a rate considered slow in relation to the seasonal, cyclical, or linear driving forces assumed to affect the marine mammal. Data capture depends on when the marine mammal surfaces and the tag can uplink to a visible satellite. It is reasonable to assume an animal will be in at least two states—active and less active—in a given time interval,  $(0, t)$ . As mentioned in Section 2.3.1, states can be defined by two parameters: displacement between two received tag positions, and turning angle between received tag positions.

A stochastic SS model will be used to explain the non-stationary variations in marine mammal telemetry data. The stochastic SS model is comprised of an observed component,  $y_t$ , and a stochastic state vector,  $x_t$ . The observed component is a time series composed of underlying trends, cyclical, seasonal, noise perturbations, error, and exogenous variable influencing components. The general form of  $y_t$ :

*General Form of the Unobserved Component Model:*

$$y_t = T_t + C_t + S_t + f(u_t) + N_t + e_t \text{ where,} \quad [1]$$

$$e_t \sim N(0, \sigma^2) \quad [2]$$

$$T_t = \text{trend component} \quad [3]$$

$$C_t = \text{sustained cyclical component} = \sum_{j=1}^{R_C} a_{j,t} \cos(\omega_j t) + b_{j,t} \sin(\omega_j t) \quad [4]$$

$$S_t = \text{seasonal component} = \sum_{j=1}^{R_S} c_{j,t} \cos(\omega_j t) + d_{j,t} \sin(\omega_j t) \quad [5]$$

$$\omega_j = \frac{2\pi j}{s} \text{ for } j = 1, 2, \dots, R_C \text{ in } C_t \text{ and } j = 1, 2, \dots, R_S \text{ in } S_t \quad [6]$$

$$f(u_t) = \text{influence of exogenous variables} \quad [7]$$

$$u_t = \text{exogenous variables} \quad [8]$$

$$N_t = \text{stochastic perturbation model} \quad [9]$$

and  $\alpha, \beta, \gamma$ , and  $\delta$  are constants used to specify the type of random walk

The observed component,  $y_t$ , is assumed to be affected by measurement error,  $e_t$  [2]. The values  $a$ ,  $b$ ,  $c$ , and  $d$  are the stochastic TVPs the algorithm seeks to solve [4,5]. This is performed via the Fixed Interval Smoothing (FIS) (Young, Pedregal, & Tych, 1999). The FIS computes the conditional expectation of a value given a set of observations. The algorithm generates a covariance matrix by looking both forward and backward in time, eventually converging to a smooth, steady state value. The only difference between  $C_t$  and  $S_t$  will be the TVPs and their fundamental and harmonic frequencies,  $\omega_j$ . In the observed component,  $y_t$ , not all components need to be included. Cyclical components or exogenous variable components are only added when they are physically meaningful to the system being forecast. This paper will investigate variations of [1] in order to smooth, interpret, and forecast marine mammal telemetry movement.

The stochastic state vector,  $x_t$ , will derive from a family of Generalized Random Walk (GRW) equations [10-14]. A GRW is a path that consists of random steps. The stochastic state vector,  $x_t$ , is  $k$ -dimensional based on the number of states. Assume a marine mammal has been tagged and being monitored over the interval  $(0, t)$ . We wish to state-decode the animal path up time,  $t$ , and then forecast the animal's predicted future state. We can define a less active state,  $x_{1,t}$ , and an active state,  $x_{2,t}$  such that the stochastic state vector becomes the higher dimension equation seen in Equation 14.

$$x_t = Fx_{t-1} + Gn_t \text{ where,} \quad [10]$$

$$F = \begin{pmatrix} \alpha & \beta \\ 0 & \gamma \end{pmatrix} \quad [11]$$

$$G = \begin{pmatrix} \delta & 0 \\ 0 & 1 \end{pmatrix} \quad [12]$$

$$n_t = \text{random Gaussian noise} \quad [13]$$

$$\begin{pmatrix} x_{1,t+1} \\ x_{2,t+1} \end{pmatrix} = F \begin{pmatrix} x_{1,t} \\ x_{2,t} \end{pmatrix} + G \begin{pmatrix} n_{1,t} \\ n_{2,t} \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ 0 & \gamma \end{pmatrix} \begin{pmatrix} x_{1,t} \\ x_{2,t} \end{pmatrix} + \begin{pmatrix} \delta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} n_{1,t} \\ n_{2,t} \end{pmatrix} \quad [14]$$

The matrices  $F$  and  $G$  define the GRW and are assumed known. By manipulating constant parameters in  $F$  and  $G$ , various types of random walks are produced. The following families of GRW are available in CAPTAIN Toolbox in MATLAB: *Random Walk* (RW:  $\alpha = \beta = \delta = 0; \gamma = 1$ ); *Smoothed Random Walk* (SRW:  $0 < \alpha < 1; \beta = \gamma = 1$  and  $\delta = 0$ ); *Integrated Random Walk* (IRW:  $\alpha = \beta = \gamma = 1; \delta = 0$ ); *Local Linear Trend* (LLT:  $\alpha = \beta = \gamma = 1; \delta = 1$ ); and *Damped Integrated Random Walk* (DIRW:  $\alpha = \beta = \delta = 1; 0 < \gamma < 1$ ).

The two equations,  $y_t$  and  $x_t$ , define the UC model. Once parameters and components within  $y_t$  and  $x_t$  are defined, the CAPTAIN employs the FIS in order to estimate  $x_t$ . A prediction of  $x_t$  is established, a conditional probability of  $x_t$  is computed,  $x_t$  is corrected based on the conditional probability, and the correction is backward passed to smooth previous predictions. During the forward pass, the model uses an autoregressive (AR) model of a user-defined order to specify that each value depends linearly on previous values. For instance, an AR order 1 depends only on the previous 1 value whereas an AR order 5 depends on the previous 5 values.

As mentioned, the  $y_t$  does not have to include all components in [1] and certain forms of  $y_t$  have names. UC models whose observed component,  $y_t$ , includes seasonal and/or cyclical components are Dynamic Harmonic Regression (DHR) models. When  $y_t$  includes only linear trends and exogenous variable influences,  $y_t$  is called a Dynamic Linear Regression (DLR) model. The CAPTAIN toolbox for MATLAB was developed at Lancaster University in order to simplify the use of DHR and DLR models for non-stationary time series analysis (Taylor, Pedregal, & Young, 2017). The toolbox is separated into Time Variable Parameter (TVP), Refined Instrumental Variable System Identification (RIV), and True Digital Control (TDC) modules that contain various algorithms models and design tools for stochastic data. This report exploits UC models from the TVP due to marine mammal telemetry's non-stationarity property. The UC models used are DHR through the functions "dhropt" and "dhr." The UC model's unobserved component has both a trend and a seasonal component based on the change of displacement (step sizes) and turning angles seen in the marine mammal telemetry track.

*UC Model for Marine Mammal Telemetry:*

$$y_t = T_t + \left( \sum_{j=1}^{R_C} c_{j,t} \cos(\omega_j t) + d_{j,t} \sin(\omega_j t) \right) + e_t \quad [15]$$

$$x_t = Fx_{t-1} + Gn_t \quad [16]$$

In Section 4.2, the UC Model is applied to a time series to track marine mammal tag movement engaging in various behaviors. For each behavior, [15] must be adjusted based on knowledge of this system such as frequency of direction change, speed change, or dependency on previous data.

### 2.3.3 Matrix Profiles (MP)

Data mining time series for trend analysis has become a popular research area in the last decade. The general data-mining framework includes: pre-process raw data, compute a similarity measure, cluster, form a representative series by cluster, and detect motifs (Baheti & Toshniwal, 2014). Motifs are reoccurring patterns within the time series data that may represent trends, behaviors, or states depending on the system. Few data mining techniques for time series are capable of mining data sets over one million observations. In 2016, the Department of Computer Science and Engineering at the University of

California Riverside and the University of New Mexico developed a novel method to lessen the computational burden for detecting exact motifs in time series: Matrix Profiling (MP) (The UCR Matrix Profile Page). Using the University of California, Riverside’s MP MATLAB suite, this paper seeks to answer, “Is there any pattern common between two tag time series.” The MATLAB script “*interactivematrixprofileAB.m*” from the Matrix Profile UCR Toolbox is used for marine mammal transmission time series.

The MP requires a z-normalized ordered data set,  $T$ , and initial subsequence length,  $m$ . The z-normal condition (zero mean and standard deviation of 1) is necessary to calculate Euclidian distances between two subsequences. Without this condition, results are poor and the algorithm may not be able to distinguish subsequences from distinct sets. The subsequence length,  $m$ , should reflect the system at hand. For example, magnetometry data was assessed from a tagged penguin. The dataset consists of 1,048,575 data points. When using a subsequence length of 2,000, the MP was able to identify 8 distinct motifs representing 8 unique dive patterns in only 2.5 minutes (Zhu et al., 2016). Other applications of MP and subsequence lengths can be seen in Table 5. A good subsequence length to begin with is  $1/20^{\text{th}}$  of the length of  $T$ .

Table 5—MP Motif Detection Performance for Various Datasets adapted from UCR Matrix Profile Page

| Dataset                                                                                                                                            | Length of Dataset, $ T $                          | Length of subsequence, $m$ | Number of motifs detected | Motif Interpretation                                                                       | Time to compute |
|----------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|----------------------------|---------------------------|--------------------------------------------------------------------------------------------|-----------------|
| Magnetometry data from a tagged penguin                                                                                                            | 1,048,575                                         | 2,000                      | 8                         | Dive behaviors                                                                             | 2.5 min         |
| Raw seismograph recording at Mount St Helens                                                                                                       | 604,781                                           | 200                        | 1                         | Seismic event (e.g. foreshocks, aftershocks, triggered earthquakes, and volcanic activity) | 34.2 secs       |
| Y-chromosome of a Chimpanzee                                                                                                                       | A little over 1,00,000                            | 60,000                     | 1                         | A recent gene duplication event                                                            | 18 secs         |
| Raw audio of “Under Pressure” by Queen and David Bowie and “Ice Ice Baby” by Vanilla Ice converted to Mel-frequency cepstral coefficients (MFCCs), | Over 5,000 observations between two MFCC snippets | 500                        | 1                         | Baseline of “Under Pressure” which was plagiarized in “Ice Ice Baby”                       | 21.9 secs       |
| Zebra Finch Vocalizations converted to MFCC                                                                                                        | A little under 8,500                              | 400                        | 3                         | Distinct vocalizations, evidence of vocabulary                                             | Under 1 min     |

The query,  $Q$ , represents the current subsequence. A Euclidian distance,  $D$ , is calculated between  $Q$  and every subsequence of length  $m$  in  $T$ . This is performed in a sliding window manner. Distance values are used as a similarity metric between subsequences. Low distance values indicate similar subsequences while high values indicate dissimilarity between subsequences. The MP algorithm expects and accounts for distance values to be low just before and at  $Q$  (Fig. 17). Once all queries are compared to all subsequences in  $T$ , a distance matrix is left. Each row of the distance matrix represents a query and each column corresponds to the subsequence to which it was compared. The smallest distances per column and indices of most similar subsequence are stored in two vectors (Fig 18). The MP is a vector,  $P$ , that stores the distances between any subsequence within a time series and its nearest neighbor (Fig. 18).

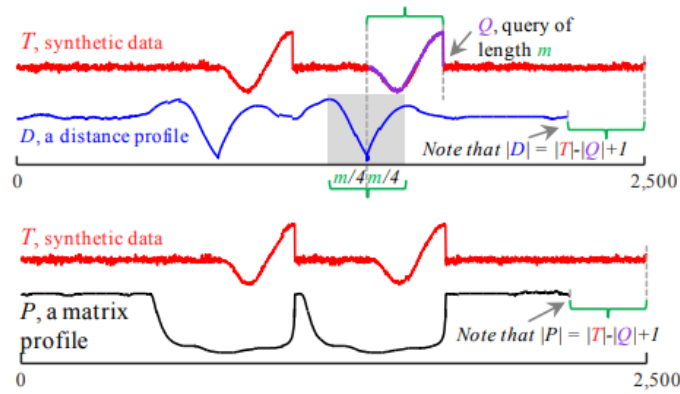


Fig. 17—Extracting a single distance profile (blue) based on a query (purple) and time series (red). Low values in the MP (black) represent motifs; patterns in the original time series. Note that the length of the distance and matrix profile is less than the length of the original time series. Adapted from UCR Matrix Profile Page.

|             | $D_1$         | $D_2$         | ... | $D_{n-m+1}$       |
|-------------|---------------|---------------|-----|-------------------|
| $D_1$       | $d_{1,1}$     | $d_{1,2}$     | ... | $d_{1,n-m+1}$     |
| $D_2$       | $d_{2,1}$     | $d_{2,2}$     | ... | $d_{2,n-m+1}$     |
| ...         | ...           | ...           | ... | ...               |
| $D_{n-m+1}$ | $d_{n-m+1,1}$ | $d_{n-m+1,2}$ | ... | $d_{n-m+1,n-m+1}$ |
| $P$         | $\min(D_1)$   | $\min(D_2)$   | ... | $\min(D_{n-m+1})$ |

Fig. 18—A distance matrix to compute,  $P$ , the Matrix Profile (MP). Each row of the distance matrix contains Euclidean distances between the subsequence query and all other subsequences in the original time series. The minimum of each column is stored in the,  $P$ . Adapted from UCR Matrix Profile Page.

The vector  $P$  can be “read” for motifs and discords. Relatively low values in  $P$  are motifs: a subsequence is similar to a least one other subsequence in the original dataset, i.e. a pattern (Figs. 17 and 18). Relatively high values in  $P$  are discords: a subsequence is not similar to any other subsequence in the original dataset, i.e. an anomaly. The locations of the two (tying) low values are the exact locations of a motif pair. Note that multiple motif pairs, triplets, or quadruplets can be found. The interpretation of a motif depends on the application and data set. Examples of motif interpretations are recorded in Table 5.

The examples described in Table 5 and in the remainder of this work use offline datasets. However, motifs and discords can be incrementally maintained for online, streaming data. The Scalable Time series Anytime Matrix Profile (STAMP) is adaptation of the previously described MP designed to allocate memory in an initial matrix profile and continuously update. An MP is advantageous because it does not require a similarity threshold; it is exact, simple, and parameter-free. Most importantly, the MP is computationally efficient, scalable, and parallelizable for any system or additional algorithm development.

This work created MPs for the SPOT 303C and SPOT 258F tag transmission recordings in Section 3.1. Tag transmission recordings will be collected from the GNU Radio SDR system described in Section 2.1, transformed to waveform time series. This report explores various subsequence lengths in order to detect and characterize common message formats between two waveforms. In this application, the interpretation of the motif is a common pattern between two tag’s transmissions.

### 3. EXPERIMENTS

The following experiments answer, “How can tag transmissions be quickly identified within a noisy environment?”, “How accurate are Argos provided positions and received RXG-134 Goniometer directions?”, and “How can available data be leveraged to simulate marine mammal movement?”

Quick signal of interest identification and time-tagging is a task required in many U.S. Navy exercises and operations. The U.S. Navy SIGINT capabilities far surpass what is provided on GNU Radio. Time-series and time-frequency domain files can be stored and processed at a far greater rate than laptop-based GNU Radio software. The benefit of Matrix Profiles (MP) is that they are parallelizable and leverage all types of hardware. A time series containing millions of data points can be generated from any system and an MP can be constructed. In Section 3.1, MPs are constructed from transmissions collected from the SPOT 303C and SPOT 258F tags.

There exists marine mammal telemetry that the U.S. Navy can readily leverage from open-source databases and researchers. The vast majority of the marine mammal telemetry posted on open-source databases or provided by researchers is processed by Argos or collected by the CLS RXG-134 Goniometer receiving system. Before the U.S. Navy begins using this data to locate or predict marine mammals in the area for mitigation purposes, the U.S. Navy must be aware of its inaccuracies. The findings in Section 3.2 agree with Boyd’s and Brightsmith’s finding that actual position errors are greater than Argos-quoted errors (2013). Section 3.2 also finds that the azimuth angle error provided by the CLS RXG-134 Goniometer system is greater than the moving marine targets stated error.

While inaccuracy in these two popular tag telemetry collection methods are greater than expected, one data point may be useful for presence of marine mammals and several data points may provide broad-scale movement of marine mammals. Consider a scenario where a U.S. Navy vessel is equipped with marine mammal tag directional finders like the CLS RXG-134/Goniometer. If the vessel receives a tagged animal location from Argos, this position can be used as an initial estimation of where a marine mammal or pod is located. Given time of year and knowledge of the species in the area, the vessel may have a general idea of where and how fast the marine mammal or pod is swimming. With the assistance of the onboard marine mammal tag directional finder, a particle filter can refine the Argos initial estimation over time. In Section 3.3, we demonstrate the effectiveness of the particle filter for predicting movement using data collected in Section 3.2.

#### 3.1 Decoding Marine Mammal Tag Messages Using Matrix Profile

The ‘*interactiveMatrixProfileAB.m*’ file searches for common patterns in a concatenated time series. By concatenating two series and designating the index where concatenation occurs, ‘*interactiveMatrixProfileAB.m*’ is able to distinguish between the two datasets when querying subsequences (Fig. 9). Using various subsequence lengths, ‘*interactiveMatrixProfileAB.m*’ is able to identify the 15 “1’s” bit sync and the 8-bit frame sync in the Argos message format from time-frequency recordings of tag transmissions. The first data set, SPOT 258F, is 5602 samples. The second dataset, SPOT 303C, is appended after the SPOT 258F dataset. The concatenated time series containing the two tag transmissions is length 65536;  $T$ . Recall  $1/20^{\text{th}}$  of  $T$  is the recommended starting sequence, which is approximately 3276;  $m$ . Using a subsequence length of 3276, the top motif captures 15 peaks of equal spacing postulated to be the Argos’s 15 ‘1’s’ Bit Sync in Table 1 (Fig. 19). Four changes in peak spacing follow the Bit Sync. After the first change in peak spacing, three peaks of equal separation occur; then the second change in peak spacing, one peak; then the third change in peak spacing, four equally spaced peaks; and finally the fourth change in peak spacing (Fig. 20). If the change in peaks represent a “bit flip”

from a 1 to a 0, the top motif captures not only the Bit Sync, but the Frame Sync and Initialization Number, 0 0 0 1 0 1 1 1 1 1, from the Argos message format.

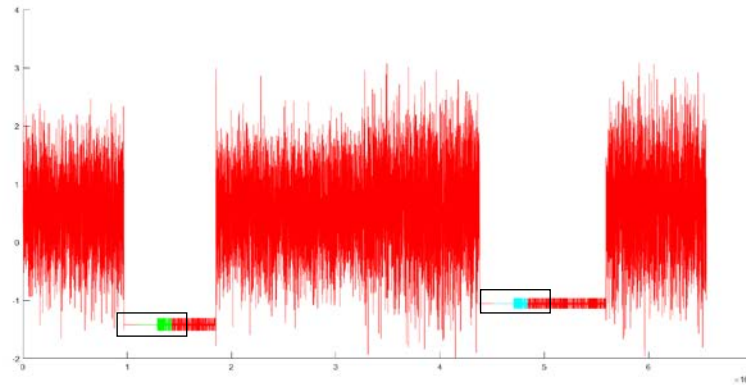


Fig. 19—Best motif (green) from the SPOT 258 message and matching pair from the SPOT 303C message (cyan). Best motif captures the bit sync, frame sync, and initialization number from the Argos message format.

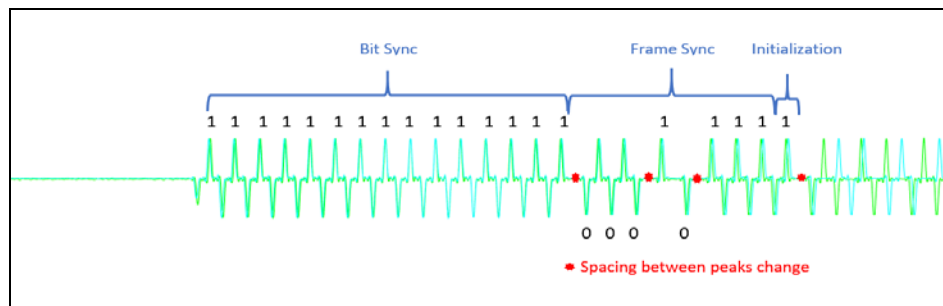


Fig. 20—Zoomed view of best motifs from Fig. 9. Postulated large spaces between peaks represent bit flips.

After the assumed Initialization Number in Fig. 20, the two tags differ. Assuming change in peak spacing denotes a binary number change, the next four bits following the Initialization Number are 0 0 1 1 and 0 1 1 0 for SPOT 258F and SPOT 303C respectively. This 4-bit sequence may very well be the part of the Sensor Numbers for each tag (Table 2). Without knowing the decoding scheme used by Wildlife Computers, the meaning of bits cannot be confirmed to be the Sensor Number. If this 4-bit stream is the tag's Sensor Number, the next 20 bits may be the "Identification and Error Checking" portion of the Argos message format, which contains the unique PTT ID for each tag. It was postulated the matrix profile algorithm would capture the PTT ID portion of the message in a discord, however all discords, regardless of subsequence length, were found within the noise of the concatenated time series. Through an empirical exploration, a subsequence length of 2000 captured the bit sync, frame sync, and initialization number. The subsequence length of 2000 removes the disharmonious data within the motif (postulated to be the tag's respective sensor number).

From the specifications provided by the manufacturer, the SPOT 303C and SPOT 258F message lengths are 64 and 32 bytes respectively. Regardless of the length of the message, the structure of the message is preserved in the MPs of the two tags. By synchronizing the two tag's profiles by their minimums, we see the first and later portions of the matrix profiles are identical (Fig. 21). The difference in samples between the absolute minimum is 1400 samples (Fig. 22). The difference in samples between the tag's rightmost local minimum is 4674 (Fig. 23). The matching portion seen in Fig. 23 corresponds to the latter portion of the Argos message: Identification and Error Checking and Sensor Data. This

matching may indicate that the two tags emitted identical errors and sensor data during transmissions. Given the transmissions were sent via the “TagAgent” in identical laboratory settings, it is likely that the errors and sensor measurements are the same. If the tags were deployed on marine mammals and in the dynamic oceanic environment, the two tags may not match in the latter portion of their MPs.

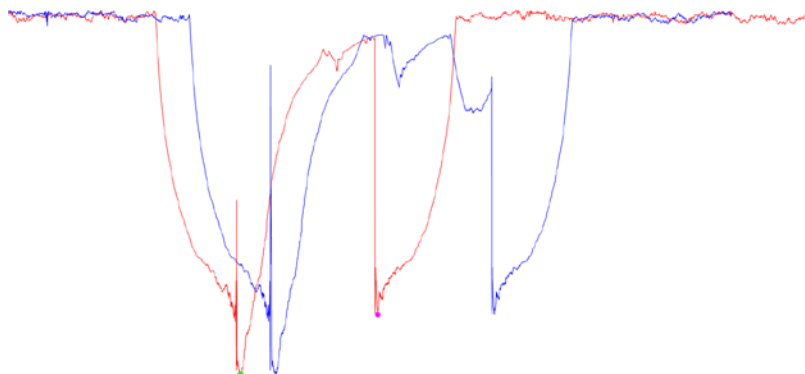


Fig. 21—Matrix Profiles (MP) for the SPOT 258F time series (red) SPOT 303C time series (blue). Green and magenta points represent absolute and local minima in the SPOT 258F MP.

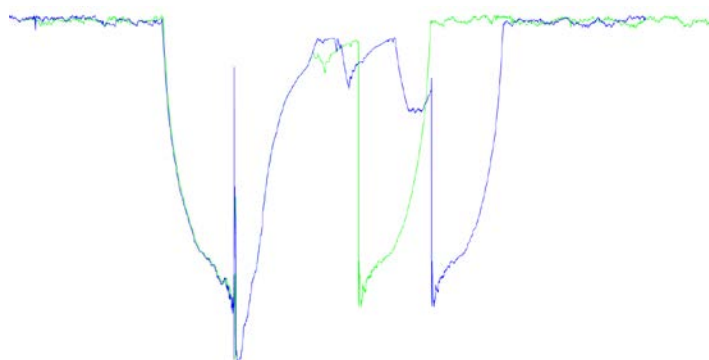


Fig. 22—Synchronized Matrix Profiles (MP) generated by shifting the SPOT 258F MP (green) right 1400 samples from its absolute minimum. SPOT 303C MP in blue.

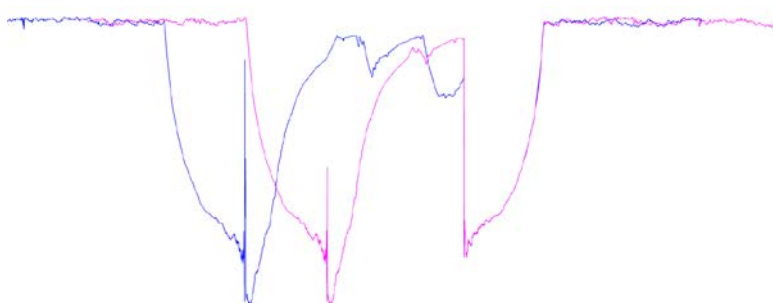


Fig. 23—Synchronized Matrix Profiles (MP) generated by shifting the SPOT 258F MP (magenta) right 4674 samples right from its local minima. SPOT 303C MP in blue.

This paper demonstrates the ease of marine mammal tag transmissions capture and collection on inexpensive SDR equipment using free SDR software. Marine mammal transmissions were processed using UCR’s Matrix Profile suite. Generating a matrix profile, searching for motifs, and analyzing

discords among large wave files took less than 30 seconds. Without any knowledge of the modulation and decoding scheme, the matrix profile identified motifs that captured the transmission message format. Each tags matrix profile was nearly identical at the beginning and end when synchronizing the two profiles.

Quickly identifying signals of interest within noisy data, timestamping occurrences, and determining signal positions or characteristics is a classic signal-processing task. Timestamping is trivial and positions may be determined by methods of time of arrival and direction of arrival. This paper explains how the signal of interest, the marine mammal transmission uplink, is identified using matrix profiles. The Argos System responsible for processing marine mammal tag transmissions has been reported to produce inaccurate and uncertain positional data. Embedding a matrix profile marine mammal transmission “detector” within collection systems could provide near real-time, marine mammal positions with little to no knowledge of Argos System. Future efforts should leverage STAMP’s ability to allocate memory and continuously update for near-real time identifications of marine mammal transmissions.

### 3.2 Evaluating Data Collection Methods for Marine Mammal Tag

On July 16, 2019, positional data from marine mammal tags was collected using commercial marine mammal tag receiving equipment. Marine mammal researchers frequently use this commercial equipment in order to recover and locate tags. The purpose of this test was to evaluate the performance of commercial marine mammal tag receiving equipment. The test was conducted at NRL’s Chesapeake Beach Detachment (CBD).

The Test Vessel (TV) is an NRL owned 22-foot Boston Whaler. The TV was used to simulate movement behavior of a tagged marine mammal. Wildlife Computers SPOT 303C and SPOT 258F tags were affixed to the vessel’s center console. Each tag was 10 feet above the water with a clear line of sight to the receiving equipment on shore (Figs. 24 and 25). The distance between the two tags was 7 feet. Tag manufacturers recommend that a tag be close to the ground plane, which in this case was the TV’s center console roof. In a trial test conducted on July 2, 2019, the TV was equipped with AIS to provide ground truth positions of the two tags. An Ashtech® DGPS was used for ground truth positions for the July 16 test because of its centimeter precision found in the stationary test, described in Section 2.2.2. The DGPS sampled at 20Hz, or every 0.05 seconds.



Fig. 24—SPOT 303C (left) and SPOT 258F (right) securely attached to vessel center console



Fig. 25—Test Vessel (TV) underway simulating ‘whale-like’ movement in NRL CBD operating area

The test consisted of four distinct runs and lasted over two hours. Descriptions of the runs can be found in Appendix D. Raw positional data for each tag was exported from Argos Web when the test commenced. During the test, tag positions posted to Argos Web within thirty minutes. The raw data files contained latitude, longitude, time of message, frequency, and Argos Location Class (LC) and error ellipse parameters. The CLS RXG-134 Goniometer receiving equipment was located on the roof of Building 1 at NRL-CBD. Building 1 is located on the cliff line South of Bldg. 75.

The runs described in Appendix D are not designed to simulate a particular marine mammal species. All vessel speeds were between 3 and 13 kts. There are a handful of species that have been seen to reach high speeds relatively close to 25 kts: sea lions at 50 kph (27 kts), orcas at 50 kph (27 kts), and the common dolphin at 64 kph (34.5 kts) (Marine Bio, 2019). Marine mammals who reach these speeds surface frequently (roughly every couple of seconds) to take quick breaths. A tagged animal engaging in this high-speed behavior is likely to have many successful tag uplinks due to frequent antenna visibility. While migrating, large whales maintain speeds between roughly 1 and 5 kts. For this Test Plan, TV was instructed to keep speeds between 3kts and 13kts, which reflect sustained swimming speeds for most marine mammals and assume an average tag uplink success rate.

In Runs 1 through 3, TV travels in straight lines and in Run 4, TV engages in a meandering, circular pattern. This does not imply that marine mammals travel in perfect straight lines and circular paths; rather, these two movements are proxies for different types of behavior. In Runs 1 and 2, TV travels directly and parallel to shore, only adjusting speed by a few knots. These runs demonstrate marine mammals traveling towards and passing through a U.S. Navy OPAREA. In Runs 1 and 2, the marine mammals are assumed to be unperturbed by any external factors. In Run 3, the vessel is instructed to travel towards shore and abruptly makes a quick turn higher speeds away from shore. This sudden change in speed and bearing demonstrates “startled” marine mammal behavior where the marine mammal may be attacking prey or escaping a predator. For simplicity, Runs 1 and 2 are denoted as ‘sustained states’ while Run 3 is a “startled” state’.

During Run 4, the vessel is instructed to simply “meander in circles” at a slow 3 to 5 kts. The vessel stays within a few hundred meter range roughly 4 nautical miles from shore. Run 4 is another proxy for a marine mammal behavior in an “encamped state.” In an encamped state the marine mammal may be breeding, feeding in a honey hole, resting, or sleeping. Tag transmission rate depends on the type of encamped behavior, and some encamped behaviors are more complex than others. Large cetaceans, such as sperm and humpback whales, have been seen to sleep vertically below the surface. While sleeping, the marine mammal’s breathing rate will drop, reducing the number of surfaces to breathe and therefore opportunities for the tag to transmit. Low data throughput is expected during a sleeping encamped state. In a feeding encamped state multiple surfaces may occur. One complex and unique behavior seen in humpbacks is “bubble-net feeding.” Groups of humpbacks will create a vortex of bubbles to disorient and consolidate their prey. Bubble-net feeding is a circular movement requiring many lunges and individuals (2–60 individuals have been seen at one time). During this feeding encamped state high data throughput is expected. If the tags were affixed to wild marine mammals engaging bubble-net feeding or sleeping, it would be expected that the tag’s wet/dry sensor would have prolonged periods of wet and dry states, therefore affecting the amount of successful tag transmissions. The tag’s wet/dry sensor was never activated in this test, so all tags transmitted regularly at 90-second intervals. If the tags were deployed on wild marine mammals, it is unlikely all tag transmissions would be successfully uplinked.

Tags transmitted throughout the entire test evaluation: Run 1 began at 12:09 UTC and the final run, Run 4, commenced at 16:21 UTC. Runs were designed such that the vessel operators could seamlessly transition from Run to Run and tags could transmit without disruption. Technical difficulties with the DGPS resulted in the exclusion of Run 1 from the final report, because ground truth data was not provided. Only data from the beginning of Run 2, 13:39 UTC; and the end of Run 4, 16:20 UTC was considered. The times of each run can be viewed in Table 6.

Positions recorded by the DGPS, Argos Web, and the RXG-134 Goniometer are summarized in Table 6. Each run contains proxies for three marine mammal behaviors: sustained, startled, and encamped. In Section 4, multistate HMMs are used to identify these behaviors within each run. Because both tags transmit at a 90-second repetition rate and the wet/dry sensors was never activated, 73 transmissions from each tag were expected between 13:39 and 16:20 UTC. This amounts to 146 transmissions total. The number of received RXG-134 Goniometer positions is equal to the expected number of transmissions per tag. At least three Argos satellites were visible during the time of test; therefore, gaps in data are expected (Fig. 6). Only 64 out of the expected 146 transmissions were reported in the raw positional data exported from Argos Web. Argos Web reported more six more positions for the SPOT 258F tag than the SPOT 303C (Table 6). The DGPS sampled at 20 Hz (i.e. every 0.05 seconds), resulting in 135,194 ground truth positions.

Table 6—Number of Marine Mammal Tag Positions Collected for Vessel Test Evaluation

| Run           | Time of Run (secs) | No. of Expected Transmissions per Tag | No. of Received RXG-134 Goniometer Positions | No. of Positions reported on Argos Web |
|---------------|--------------------|---------------------------------------|----------------------------------------------|----------------------------------------|
| 2             | 3579               | SPOT 258F: 39<br>SPOT 303C: 39        | SPOT 258F: 39<br>SPOT 303C: 39               | SPOT 258F: 19<br>SPOT 303C: 15         |
| 3             | 2219               | SPOT 258F: 24<br>SPOT 303C: 24        | SPOT 258F: 24<br>SPOT 303C: 24               | SPOT 258F: 10<br>SPOT 303C: 10         |
| 4             | 960                | SPOT 258F: 10<br>SPOT 303C: 10        | SPOT 258F: 10<br>SPOT 303C: 10               | SPOT 258F: 6<br>SPOT 303C: 4           |
| <b>Totals</b> | 6758               | 146                                   | 146                                          | 64                                     |

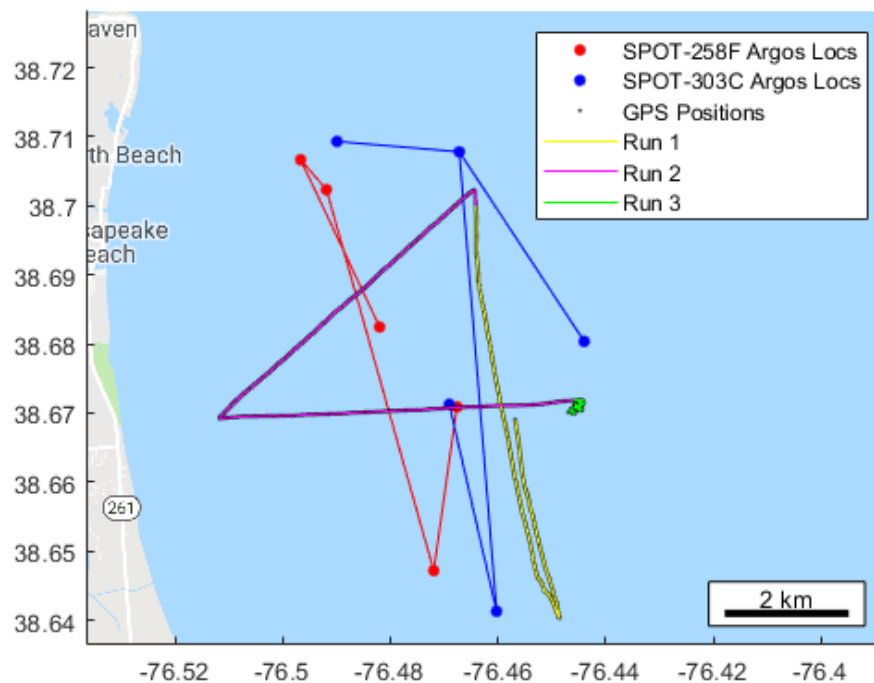


Fig. 26—Test Vessel (TV) runs designed to simulate marine mammal movements. Ground truth positions of vessel are color coded by distinct runs and compared to Argos Web Locations. Y-axis is longitude and x-axis is latitude.

The average distance between the DGPS ground truth positions and SPOT 258F Argos Web positions was  $2.71 \pm 0.73$  km. The distance error was lower for the SPOT 303C tag:  $1.19 \pm 0.66$  km. Of the Argos Web positions reported, many coordinates were duplicates. There were only five unique coordinates for both the SPOT 258F and SPOT 303C tag across Runs 2, 3 and 4. Latitude and longitude values from Argos Web and values from the DGPS at the Argos Web timestamp are shown in Figs. 27 and 28. Run 2 is captured in samples 1–18, Run 3 is captured in samples 18–29 and Run 4 is captured in 29–36 (Figs. 27 and 28). Note that less positions were received for the SPOT 303C tag then the SPOT 258F tag, hence why the plots extend longer for the SPOT 258F tag in Figs. 27 and 28. Argos Web latitudes seem to provide a general shape of the true DGPS latitudes more accurately than the Argos Web longitude data and true DGPS longitudes. The average error between the DGPS latitude and longitude data for the SPOT 258F tag was 0.00984 and 0.0278 decimal degrees respectively. Argos Web latitude and longitude error for the SPOT 303C tag was less: 0.00830 and 0.0106 decimal degrees error for latitude and longitude.

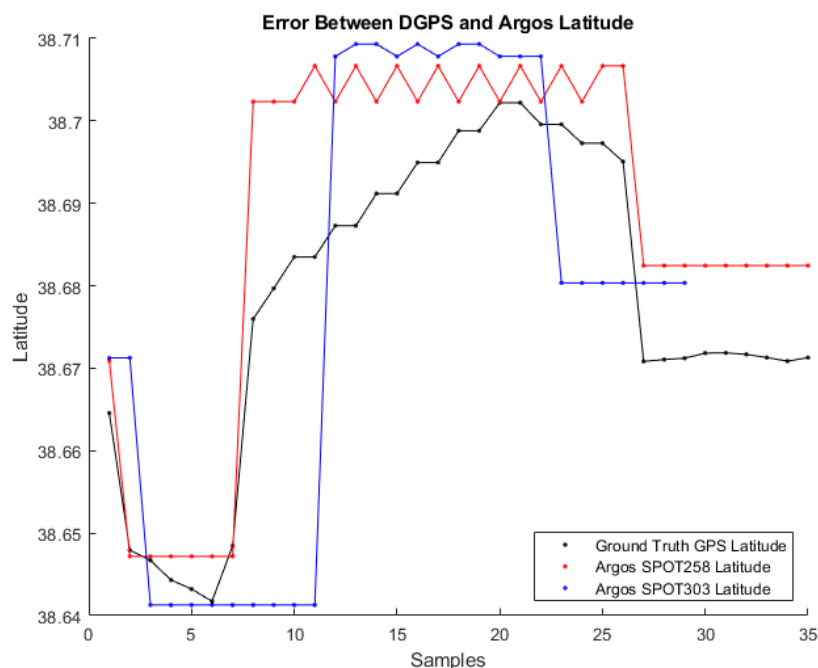


Fig. 27—Argos Web Latitude values for each tag type compared to ground truth DGPS latitudes. Y-axis is latitude values in decimal degrees and x-axis is sample number.

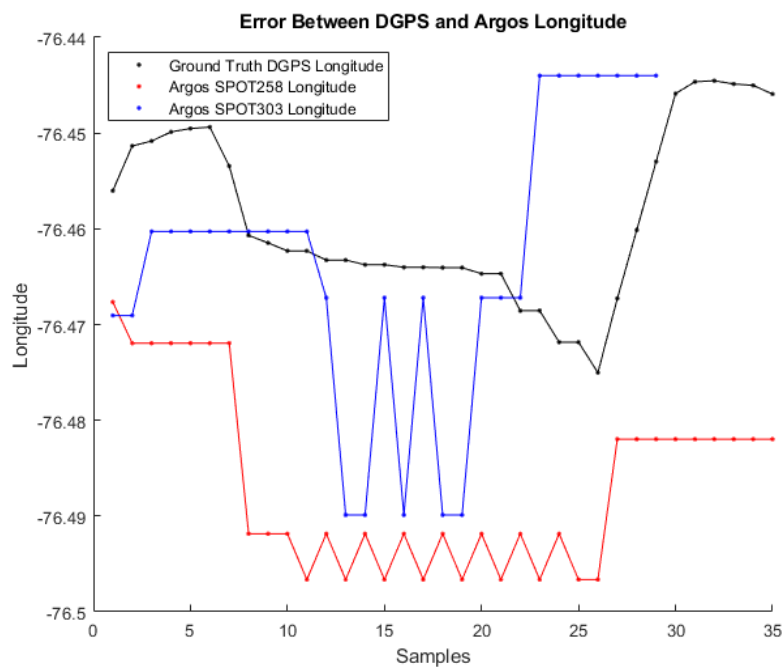


Fig. 28—Argos Web Longitude values for each tag type compared to ground truth DGPS longitude. Y-axis is longitude values in decimal degrees and x-axis is sample number.

Of the Argos Web locations, only 4.6% were of the highest accuracy, LC 3. No LC A and B were reported. Half of the locations were LC 2, which have an estimated error between 250 and 500 meters (Table 2). In Figs. 29 and 30, most the LC error ellipses do not encompass the true DGPS position. Only

two error ellipses out of the 64 Argos reported positions encompassed the true DGPS positions, both of which were LC 1, whose estimated error is between 500 meters and 1.5 kilometer according to Table 2.

The tags were known to be 7 feet apart, yet the Argos Web latitude and longitude positional error between tags average latitude error was 0.0157 decimal degrees (~1.7 km) and average longitude error was 0.0240 decimal degrees (~2.7 km). The longitude errors' tendency to be higher than the latitude errors confirms observations reported in Dubinin et al., 2010; Vincent et al., 2002; Soutullo et al., 2007; Costa et al, 2010; and Boyd & Brightsmith, 2013.

Table 7—Argos Location Class (LC) Evaluation

| Run Number | No. ArgosWeb Positions per Tag | 3 | 2  | 1  | 0 | No. of Accurate LC |
|------------|--------------------------------|---|----|----|---|--------------------|
| Run 2      | SPOT 258F: 19                  | 1 | 12 | 6  | 0 | 0                  |
|            | SPOT 303C: 15                  | 2 | 2  | 2  | 9 | 1                  |
| Run 3      | SPOT 258F: 10                  | 0 | 7  | 3  | 0 | 1                  |
|            | SPOT 303C: 10                  | 0 | 7  | 3  | 0 | 0                  |
| Run 4      | SPOT 258F: 6                   | 0 | 0  | 6  | 0 | 0                  |
|            | SPOT 303C: 4                   | 0 | 4  | 0  | 0 | 0                  |
| Totals     |                                | 3 | 32 | 20 | 9 | 2                  |

Figures 29–31 show each Run's true DGPS positions, Argos Web positions, and Argos Web reported error ellipse. The error ellipse parameters, the semi major axes, and the semi minor axes are reported in the Argos Web raw data. One hundred simulated points are uniformly sampled within the error ellipse to show possible tag positions. In Figs. 29 and 30, overlap between the Argos error ellipse and the ground truth DGPS is shown. This overlap shows the two “accurate” LCs reported in Table 7. The sparsity of points across Figs. 29–31 is due to the many duplicate Argos Web points. Figure 31 only has two unique Argo Web positions and neither of their error ellipse encompass the true Run 4 track.

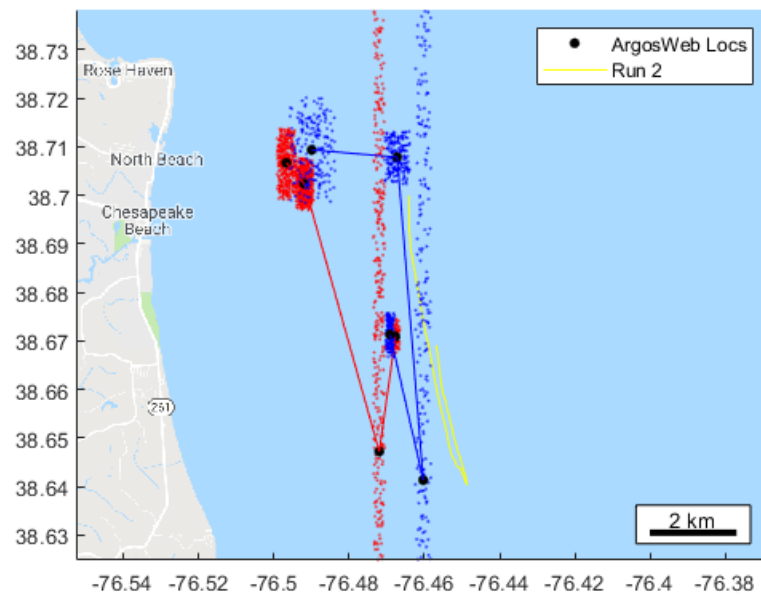


Fig. 29—Test Vessel (TV) Run 2 track (yellow) compared to received Argos Web locations error ellipse for the SPOT 303C tag (blue) and SPOT 258F tag (red). In Run 2, the vessel travels south of coastline at 3kts then turns north of coastline at 8kts.

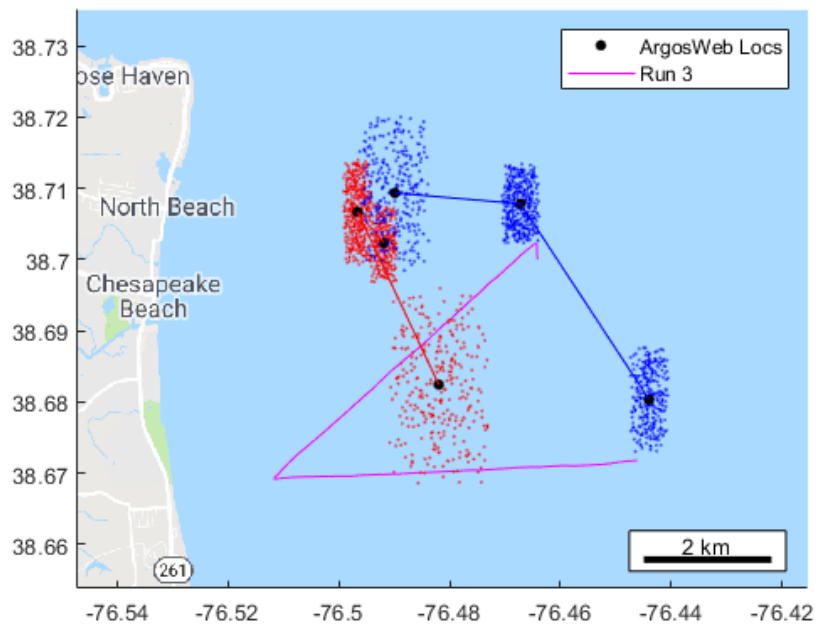


Fig. 30—Test Vessel (TV) Run 3 track (magenta) compared to received Argos Web locations error ellipse for the SPOT 303C tag (blue) and SPOT 258F tag (red). In Run 3 the vessel travels towards coastline at 8kts then abruptly turns away from coastline at 13kts.

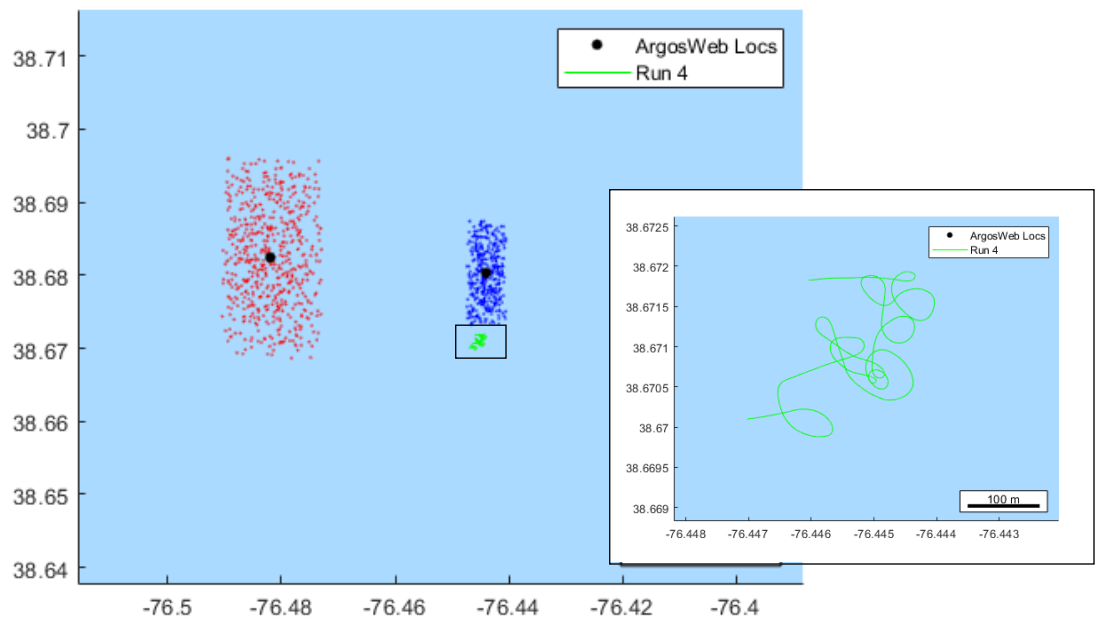


Fig. 31—Test Vessel (TV) Run 4 track (green) compared to received Argos Web locations error ellipse for the SPOT 303C tag (blue) and SPOT 258F tag (red). A zoomed view of Run 4 is offered in the right-hand plot. In Run 4 the vessel meanders in a circular pattern at 3 to 5 kts.

The RXG-134 Goniometer calculates the direction of tag using its onboard GPS and received power of tag transmission. The DGPS was used to provide an accurate true GPS reading of the Goniometer antenna: 38.657694 latitude and -76.528522 longitude. The RXG-134 Goniometer onboard GPS calculated its position at 38.657666 and -76.528299. The difference in GPS reading should have little effect on the direction of tag calculation. True direction between the Goniometer antenna and TV was calculated using the position of antenna and DGPS positions (Fig. 32).

The average signal power of the tag transmissions received by the Goniometer antenna was -97 dbm. The antenna was not adjusted and the RX-134 was in hyperterminal mode so that received transmissions could appear on the device in real time. The RXG-134's compass was calibrated prior to beginning the test and was receiving tag transmissions well before the start of Run 2. The directional error between the Goniometer antenna and DGPS and direction reported by the RXG-134 was 35.7 degrees (Fig. 32).

Between samples 1 to 37, the TV was in Run 2 and the planned turn around occurred roughly halfway through the tun as expected. During Run 3 (Samples 37 to 52), the TV traveled straight to shore and turned, changing its angle relative to the Goniometer antenna slightly. In Run 4, the TV meandered in a circle motion in a roughly 250-meter bounding box (samples 52 to 70). The known TV change of direction in Runs 2 and 3 is shown in Fig. 32. Slight variations in TV angles can be seen during Run 4. During the test, the majority of direction angles reported by the RXG-134 fell between 56 and 59 degrees. The average angle error between the true and RXG-134 angles respectively was 34.82 and 34.40 degrees for the SPOT 258F and SPOT 303C tags.

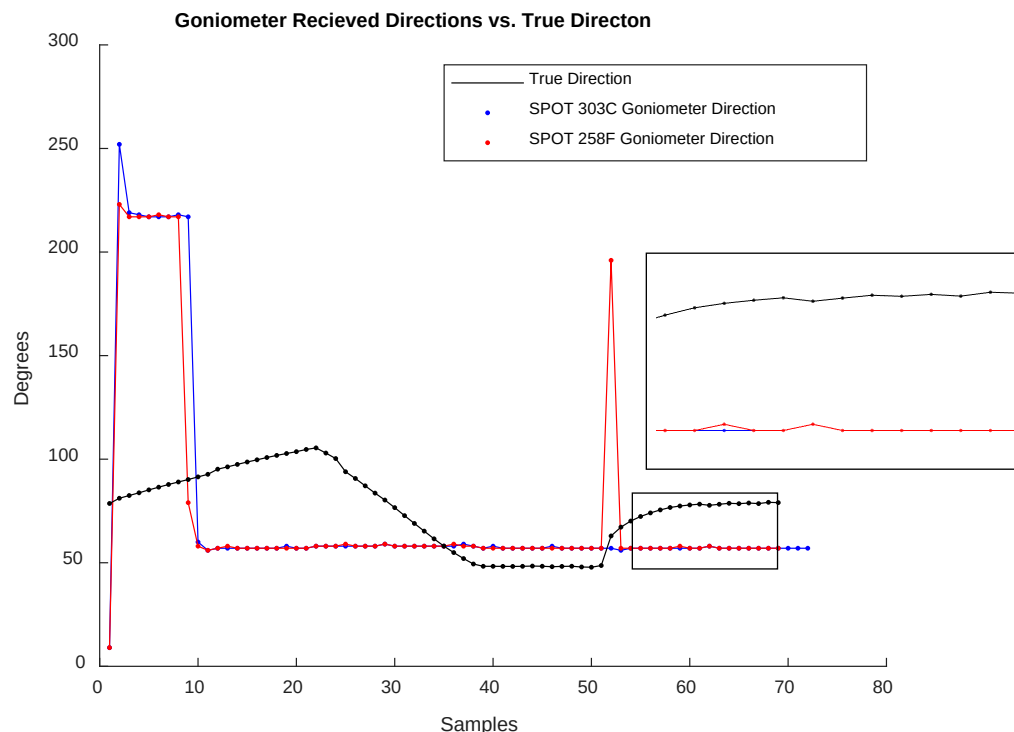


Fig. 32—Goniometer/RXG-134 direction angles shown against true direction of tags where blue points depict the received SPOT 303C direction and red points depict the received SPOT 258F direction. A zoomed view of Run 4 is shown. The y-axis is longitude values in decimal degrees and the x-axis is sample numbers.

While the positional and directional error between the Argos Web, Goniometer/RXG-134 receiving system, and true positions and directions is significant, the Argos Web and Goniometer/RXG-134 can still be used to report presence of a marine mammal. Presence of a marine mammal is valuable given that marine mammals are elusive and difficult to detect. Presence should be used to generate a likelihood of marine mammal detection. As more marine mammal detections are provided, the initial location can be refined using nonlinear filtering methods to forecast marine mammal movement. The nonlinear filtering method used in Section 3.3 is the Particle Filter (PF), allows error and prior knowledge to be incorporated into the modeling procedure.

#### 4. MODELING

Various methods exist to model noisy, nonlinear data such as marine mammal detections. The PF is a Bayesian filtering algorithm that assumes measurements are affected by noise and error. The PF generates a particle cloud over a likely region, predicts, updates, weighs, and estimates the likely position using prior knowledge of the system. Section 4.1 applies knowledge of the inaccuracies in the RXG-134 Goniometer system and Argos Web locations as prior knowledge in the PF algorithm. Section 3.2 describes the inaccuracies of the Argos web positional data. It is not meaningful to apply behavioral classification and forecasting models to such a sparse positional dataset. Therefore, multistate HMMs and the UC model are applied to the DGPS ground truth data to demonstrate the capabilities of the algorithms for interpreting marine mammal movement. In Section 4.2, 2, 3 and 4-state HMMs efficiently classify each TV Run by the expected speed and direction. Finally, in Section 4.3, a UC model is applied to the DGPS dataset to demonstrate its ability to interpolate missing data, a frequent observation in marine mammal tagging studies.

#### 4.1 Particle Filtering with Argos and RXG-134 Goniometer Positions

Marine mammal fieldwork and literature provide a general idea of marine mammal migration routes, feeding and breeding hot beds, and behavior in the presence of anthropogenic stressors. Given a location, time of day, time of year, and species type, it is reasonable to assume the marine mammal's behavior or state. For instance, the humpback's migration route is well over a thousand kilometers. As the humpbacks travel south to low latitudes in the winter for breeding, researchers have observed the species over-winter in the Mid-Atlantic. The Mid-Atlantic offers a supplemental feeding ground to the high latitude polar regions for humpbacks. Even though the humpbacks travel thousands of kilometers, there is a high probability that the humpbacks will visit the Mid-Atlantic to feed just outside the Chesapeake Bay from February to April.

Marine mammals reside below the surface for hours at a time before briefly surfacing. Even if the marine mammal breaches the surface, its dorsal or fluke fins may be masked in rough seas or weather. In rough conditions, a marine mammal observer may miss the brief surface. Many marine mammal species travel in groups. Some species' migration routes, feeding, and breeding areas have yet to be defined. There are many uncertainties in marine mammal research. Tracking marine mammals is a multimodal, nonlinear problem affected greatly by measurement noise and unknown processes. Therefore, any presence information is valuable.

The properties of the marine mammal tracking problem are appropriate for study by the PF algorithm. The PF is an extension of the KF, where a conditional probability is given based on each measurement, and each measurement depends on previous observations and prior knowledge (Waqar, 2019). Prior knowledge in the KF and PF could be physical parameters that the system is expected to be follow. This could include the effect of gravity, wind speeds, kinematics, mechanics of the device, power, etc. What differentiates the PF from the KF is the use of random sampling. The PF algorithm is initiated with a prediction, and then particles are randomly distributed over that prediction to create a particle cloud. If marine mammal detections are desired, begin by randomly generating many particles over a large region where the marine mammal is likely located. Refine the initial particle cloud as more detection data is received. The particle cloud is updated by the assumed trajectory of the marine mammal. Each particle's position is then updated and weighed. The weighing function Bayes rule and assumes both prior knowledge and a likelihood function. After each particle is weighed, a new estimate and resampling of particles is required. This process continues as long as prior knowledge and likelihood is available.

The ArgosWeb locations and received RXG-134 Goniometer tag angles can be used to generate the initial particle cloud and compute the likelihood of each particle. Prior knowledge of the TV speeds and bearings presented in Section 3.2 are used to update each particle. This prior knowledge of a vessel's speed or bearing is synonymous to knowledge of a marine mammal species' maximum speed, migratory route, historical feeding ground, etc.

An Argos Web location was used to generate initial particle cloud (Fig. 33). Uniformly distributed particles are generated within the Argos Web location's error ellipse. An Argos Web location of LC 3 will have smaller particle cloud than an LC 0 because its error ellipse is smaller. If an Argos Web LC 3 location is used for an initial estimate, it is postulated the PF will converge quicker to the true location than if a LC 0 location was used. In Fig. 33, an Argos Web LC 3 location was used as an initial estimate and one thousand uniformly distributed particles are generated within a LC 3 error ellipse.

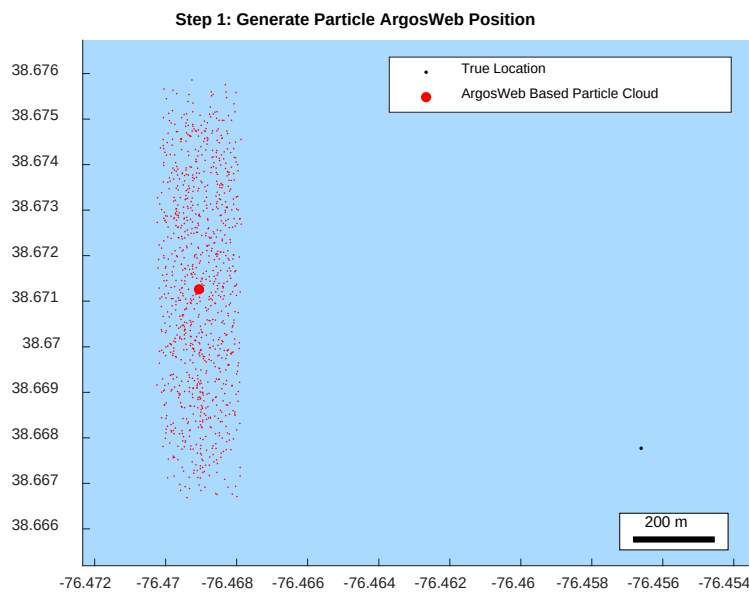


Fig. 33—One thousand particles generated around an ArgosWeb LC 3 location during Run 2. True location of vessel with tags at Argos Web location timestamp is black point.

The particle cloud was then updated using the parameters of Run 2. In Run 2, the TV traveled south at 3kts and turned halfway through the run at 8 kts (Fig. 34). Each particle was updated based on this simple trajectory and measurement noise was added (Fig. 34). The updated particles were then weighed by additional prior knowledge: the RXG-134 Goniometer direction angles. The RXG-134 claims to have a range of 100 km and angle resolution of 1 degree. Using these parameters, a likelihood range was generated (Fig. 35). A Euclidean distance between the likelihood range and updated particle distance was calculated for each updated particle in the previous step. Weights were calculated and normalized using Bayes' Theorem. Only the 100 highest weighted particles were used in the resampling method. Using the 100 “best” particles, an estimate was computed based on average position. The PF algorithm generated a new particle cloud based on the estimate and predicted, updated, weighed, resampled, and estimated the true position of the tags until Run 2 ended or no RXG-134 Goniometer was provided. The final PF track for Run 2 based on an initial ArgosWeb LC 3 location is shown in Fig. 36.

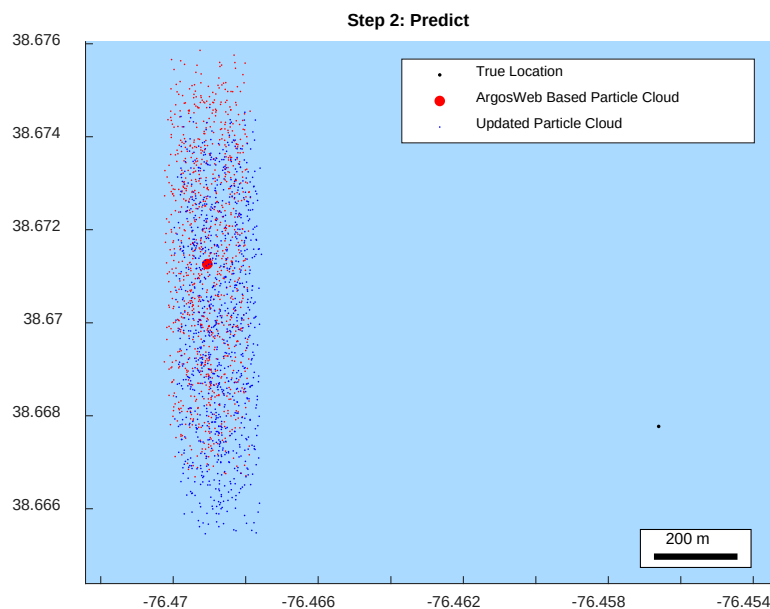


Fig. 34—Particle cloud from Step 1, updated based on the 3kt and 8kt speeds and sound/north bearings of the vessel during Run 2 (blue points). True location of vessel with tags at Argos Web location timestamp is the black point.

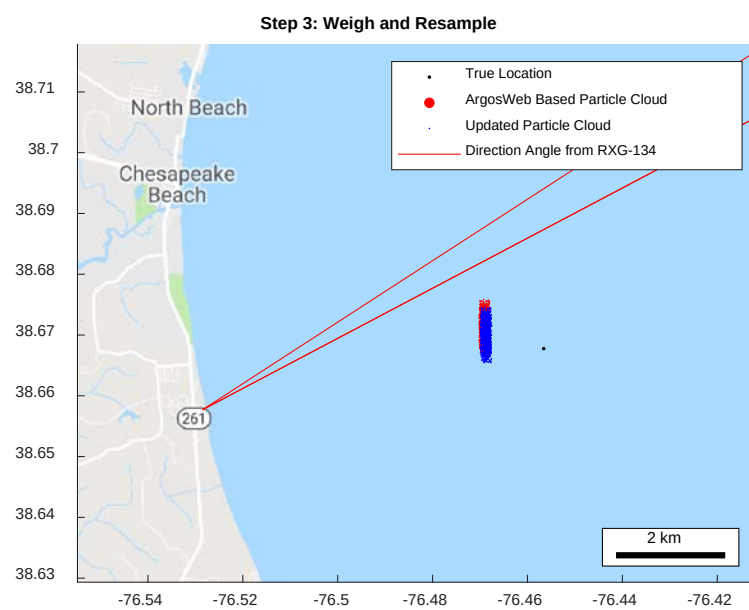


Fig. 35—Updated particle cloud from Step 2, is weighted based on received angle from Goniometer/RXG-134 receiving system (red triangle range). True location of vessel with tags at Argos Web location timestamp is the black point.

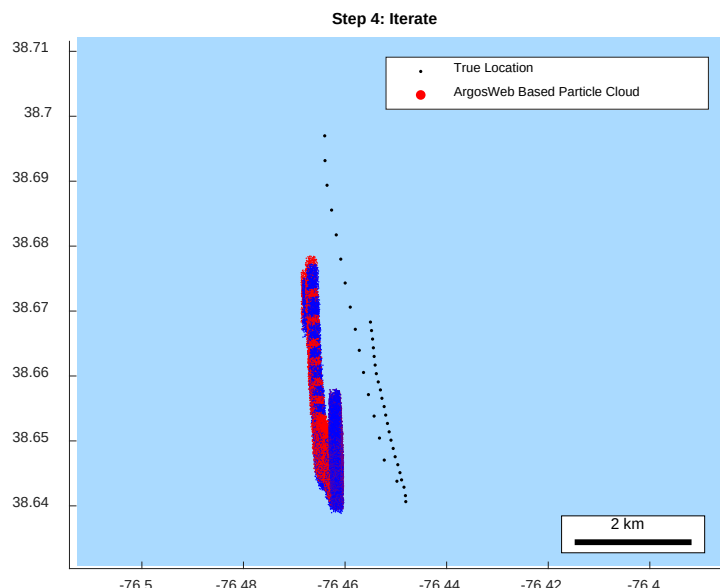


Fig. 36—Steps 1–3 iterated until completion of TV Run 2. The PF track is shown by red and blue generated and updated particle. True locations of vessel are represented by the black points.

The range of the Goniometer antenna and accuracy of the initial Argos Web position were explored using the PF method. As expected, initial positions with larger error ellipses generated inaccurate tracks. The range of the Goniometer antenna should be based on geographic region. A one-kilometer range encompasses the width of the Chesapeake Bay, and so the PF track is within the Chesapeake Bay. If a 100 km range is used, the PF track in this scenario goes over land. Decreasing the accuracy of the antenna from 1 to 5 degrees significantly improved the track estimation, but decreasing accuracy 5 to 40 degrees did not significantly impact the estimated track trajectory.

The PF algorithm described does not incorporate the ground truth DGPS points. The PF track in Fig. 36 only offers a general movement of Run 2. This application could be applied using other marine mammal detection data. Instead of using Argos Web locations as an initial estimate, the RXG-134 Goniometer (or other directional finding equipment for tag transmissions) could also be used as a basis to generate the initial particle cloud. Shipboard or aerial surveys may also be used as an initial estimate or when weighing particles. The PF's proficiency depends on the quality of data. Accurate and dense marine mammal detection data generates an accurate trajectory track. Figures 33–36 were created based on the kinematics of Run 2; however, the same process could be applied to Run 3. The more nonlinear the track, like Run 4, the more inaccurate the PF estimates are. Therefore, the PF algorithm should primarily be used to predict linear marine mammal movement behavior such as migrating.

## 4.2 Hidden Markov Models (HMM) for Marine Mammal Behavioral Analysis

The use of Hidden Markov Models (HMM) was inspired by the EcoHMM, a group of researchers who apply HMMs to wildlife tag data. Humpback tracks from the Mid-Atlantic Humpback Whale Monitoring Studys were used to explore HMM capabilities. HDR Inc. and Naval Facilities Engineering Command (NAVFAC) Atlantic aimed to assess the abundance and congregations of humpback whales in specific high-traffic and/or high-use U.S. Navy training areas during this study. From January 2015 to March 2018, HDR Inc. Virginia Beach researchers captured photographs for a humpback identification database, collected biopsy samples, conducted focal follows, and deployed 39 *Wildlife Computers* SPOT6 and 5 *Wildlife Computers* SPLASH10-5-333 *Fastloc* satellite tags (Aschettino & Englehaupt, 2019).

S2A's vessel database dates back to May 2017 and only 6 out of the 44 tags deployed by HDR begin after May 2017. A total of 7,853 vessel tracks were found within the vicinity of the 6 whale tracks from the October 31<sup>st</sup> 2017 through February 13<sup>th</sup> 2018 timeframe. For this HMM application, only these 6 tags were used. The presence of vessels, depth, and distance to coast were covariates considered to effect the behavior of humpbacks within tracks. Each HMM assumed "step sizes" (e.g. distances between tag positons) to be Gamma distributed with parameters  $k$  and  $\theta$  and "turning angles" (e.g. angles between tag positons) to be von Mises distributed with parameters  $\mu$  and  $\kappa$ . The Gamma parameters were in kilometers whereas the von Mises parameters were in radians. Out of the 2 and 3-state HMM, the 3-state HMM proved superior by goodness of fit.

For each state in the 3-state HMM, a 95% confidence interval was provided for all step size and turning angle fit parameters. The 3-HMM defined State 1 as an encamped state with the following fit parameter intervals:  $k = (3.5, 4.3)$ ,  $\theta = (2.4, 3.0)$ ,  $\mu = (-0.9, 0.8)$ , and  $\kappa = (0.07, 0.4)$ . State 2 was a significantly encamped state with fit parameters,  $k = (1.5, 2)$ ,  $\theta = (0.9, 1.4)$ ,  $\mu = (1.9, 3.9)$ , and  $\kappa = (0.08, 0.50)$ . Finally, State 3 was a transiting state with fit parameter,  $k = (9.6, 14)$ ,  $\theta = (9.1, 14)$ ,  $\mu = (-0.2, 0.2)$ , and  $\kappa = (1.1, 1.9)$ . The 3-state HMM produced transition matrices to compute the probability from switching between states given a covariate (Fig. 37). The HMM concluded the number of vessels near the tagged marine mammal and distance to coast had no effect on the humpback transition between states. The only covariate whose transition matrix showed a linear trend was depth (Fig. 37). If the humpback was in State 1 and in deep water, there is a high probability the humpback would switch to State 2.

Continuous Random Effect of Covariates on State-Dependent Probabilities

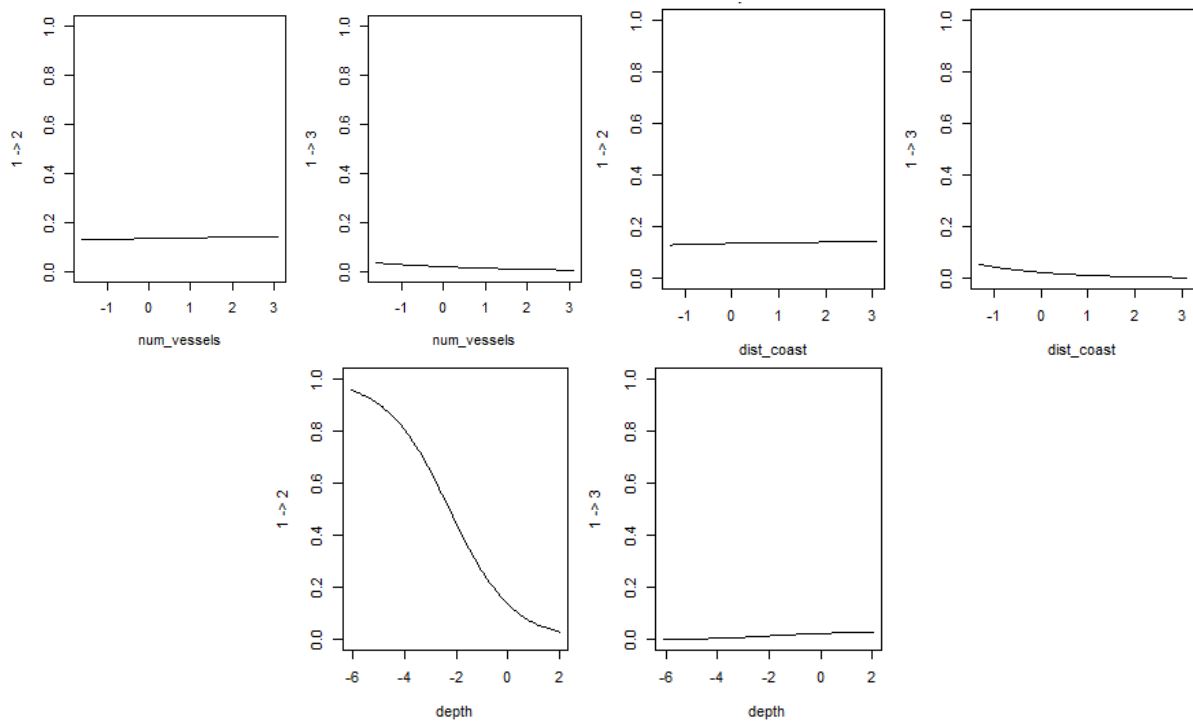


Fig. 37—Probabilities of state switch for 3-state HMM model applied to humpback tracks from the Mid-Atlantic Humpback Whale Monitoring Study. Graphs depict the likelihood the humpback will switch between States 1,2, and 3, as covariates such as depth, distance to coast, and number of vessels are introduced (all normalized values in the x-axis).

The tags used in the Mid-Atlantic Humpback Whale Monitoring Study were Argos-based marine mammal tags similar to those used in this paper. Without having any ground truth on these six humpbacks, there is no conclusive evidence that the relationships between marine mammal state switching and covariates are accurate (Fig. 37). There is also no way of knowing how accurate each Argos position was and the HMM results should be questioned.

Using knowledge of the vessel runs from Section 3.2, three multi-state HMMs were fit to the ground truth DGPS data to detect changes in speed, turning angles, and overall behavior of the vessel. Instead of vessel runs being evaluated individually, this section combines runs 2, 3, and 4 into a single nearly 2-hour long dataset. This is possible because during the test, the vessel made quick, smooth transitions from one run to the next. Within the nearly 2-hour DGPS dataset, the vessel was instructed to travel at three different speeds: 3, 8 and 13 kts, or 1.54, 4.12, 6.69 m/s; make two distinct turns and change of speeds; and meander for just over 15 minutes.

The DGPS data was down sampled to a sample per second and 90 seconds. The latter sample rate is the pulse repetition rate of the tags. Multi-state HMMs were applied to the two down sampled tracks in order to evaluate whether the HMMs behavior decoding was consistent across various sample rates. The 90-second down-sampled DGPS track presents what the ArgosWeb positions should have generated given all transmissions were received and geo-located at the highest accuracy. The change in sample rate changes the initial parameter values that initiate the HMM algorithm. This required either a general idea of the speeds and directions of the vessel during the test. For example, for a 1 second sample rate for a 2-state HMM, initial step size parameters (or distances between two samples) were  $1.5 \pm 0.05$  m/s (3 kts) and  $4 \text{ m/s} \pm 0.5$  (8kts). Standard deviations were arbitrary. Because the track consisted mainly of straight paths, one of the initial turning angle parameters was set to 0 radians (angle between one sample and the next was relatively unchanged). The track also contained turns where the vessel made a 180-degree turn; therefore,  $\pi$  radians was the other turning angle parameter for the 2-state model. The 3-state and 4-state models initial step size parameters were established in a similar framework as the 2-state model: 3 and 4 step size parameters between 0 and 10 meters were offered for the 1 sample rate dataset, and 3 and 4 step size parameters between 100 and 1000 meters were offered for the 90-sample rate dataset. For the 3-state and 4-state models, initial turning angle parameters between 0 and  $\pi$  resulted in HMM convergence. These ranges were found empirically. As long as the initial parameters were realistic speeds and turning angles for the system and the initial parameters corresponded to the sample rate, all HMM models converged to a solution. In the case of marine mammal, an unrealistic initial parameter would be a step size of well over 17.8 m/s (64 kph), which is the fastest speed ever documented by a marine mammal.

For the 2-state HMM, the authors postulated whether straight travel lines seen in Runs 2 and 3 could be distinguished from the circular, meandering behavior seen in Run 4. The 3-state model was applied to evaluate whether the HMM could distinguish the three distinct runs from each other. Finally, the 4-state HMM was used to evaluate whether the HMM could distinguish not only the three distinct runs but the changes in speeds and direction presented in Runs 2 and 3 (Appendix D).

Each  $m$ -state HMM generates expected step size and turning angle parameters for each state. All HMM's assume step size follow a gamma distribution with two parameters, shape,  $k$ , and scale,  $\theta$ , and turning angle follows a von Mises distribution, location,  $\mu$ , and concentration  $\kappa$ . In Figs. 38–40, probability density function fits for a 4-state HMM are shown where a set of step size and turning angle fits represents a state. In Fig. 38, four gamma probability density function are fit to the step size distribution. In Fig. 39, four von Mises probability density function are fit to the turning angle distribution. Both the step size and turning angle distributions derive from the 90-sample rate DGPS dataset. State 1 is defined by step sizes between 617 and 622 and turning angles narrowly set at 0 radians. In context to the vessel test, this state corresponds to when the vessel was traveling straight at 13 kts in Run 3 (617 meters per 90 seconds is equivalent to 13.32 kts). State 2 is defined by step sizes between 144

and 146 and turning angles centered at 0 with a slightly larger range than in State 1. State 2 corresponds to the beginning of Run 2 when the vessel is traveling south at 3 kts. State 3 captures a wider range of step sizes, 124 to 250 or 2.68 and 5.40 kts and almost uniform variation in turning angles. The uniform turning angles indicates frequent turns. State 3 follows the exact instructions of Run 4: “TV circles randomly for 15 mins between 240 T and 290 T maintain 3 nm distance from goniometer. Speed kept between 3 and 5 kts” (Appendix D). Interestingly, locations where the vessel turned and increased speed were defined as State 3 (Fig. 40). Finally, State 4 is defined by step sizes between 382 and 399 or 8.25 and 8.61 kts with turning angles centered at 0. State 4 corresponds to the portions of Run 2 and 3 where the vessel is traveling straight at 8kts.

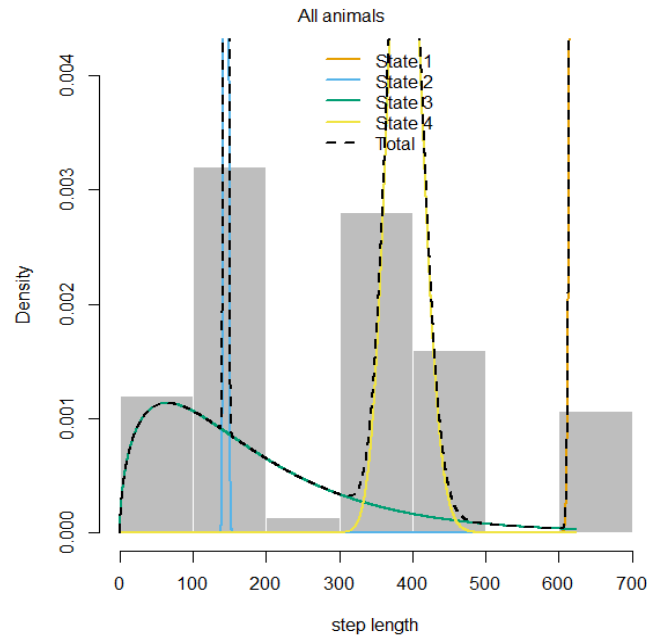


Fig. 38—Gamma distribution fits for the 4-state HMM. Fits are colored by state and gray histogram, represents actual step size values in meters from the DGPS track sampled every 90 seconds.

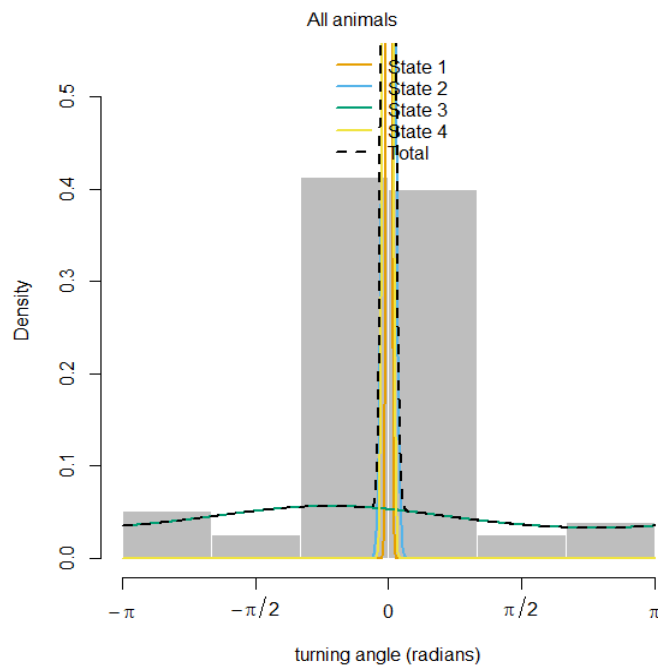


Fig. 39—Von Mises distribution fits for the 4-state HMM. Fits are colored by state and gray histogram, represents actual turning angle values in radians from the DGPS track sampled every 90 seconds.

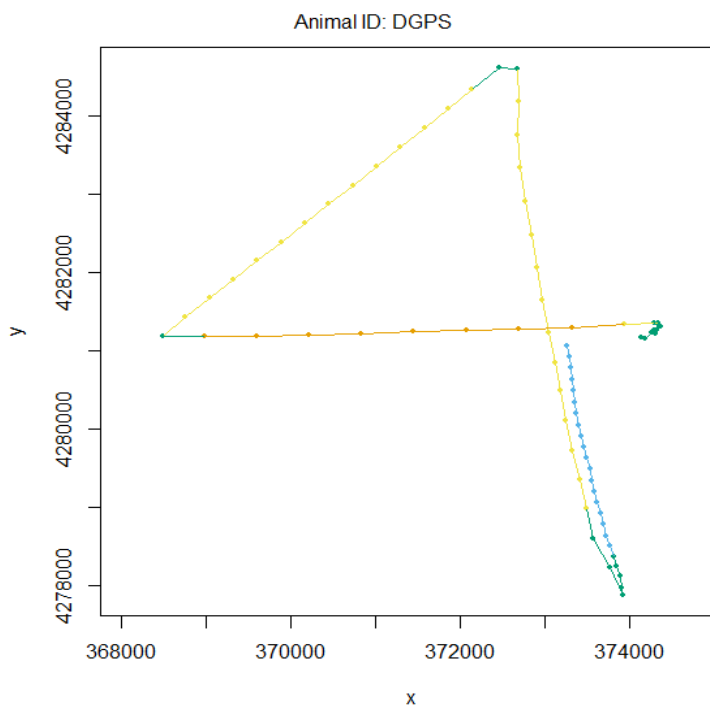


Fig. 40—Full DGPS track containing Runs 2, 3, and 4 and colored by states. Orange, blue, green and yellow points correspond to States 1, 2, 3 and 4 respectively. X-axis is in Easting and Y-axis is in Northing.

Step size and turning angle parameters for 2-, 3-, and 4-state models are displayed in Table 8. According to the AIC, the best model was a 4-state HMM with one sample per second. In fact, the more states and data points, the better the model. This is an example of Michelot's, Langrok's, and Patterson's warning that the AIC tends to favor the overly complicated models (2016). The 4-state HMM with one sample per second defines only 4 locations to be State 1 and is barely noticeable in the color-coded state graph in Fig. 43. The majority of data points are defined as State 4: step sizes around 9 kts and turning angles centered at 0. In context of the vessel test, the 4-state HMM for a 90 seconds sample rate is the best model because the state decoding captured almost exact magnitudes of speed, changes in speed, and changes in direction.

In Figs. 41 through 42, it is clear that down sampling the data set does not affect how the HMM state decodes. As expected, the more data points, the higher confidence and the narrower the interval. This relationship can be seen in the 2-state and 3-state model parameter values in Table 8. For the 4-state HMM down sample, state definitions are not preserved as seen in the 2 and 3-state models. State 1 in the 4-state 90 second sampled data encompasses the entire 13 kt, straight path seen in Run 2 where State 1 in the 4-state 1 second sampled data is a mere 4 points (Fig. 42).

Across the  $m$ -state HMMs, the labeling of states is not the same and may be misleading. By investigating the parameter values in Table 8 similar states appear across all  $m$ -state HMMs. For example. The parameter intervals for State 2 in the 2-state, State 3 in the 3-state model, and State 4 in the 4-state are identical (Table 8). However, as more states are introduced, data points labeled State 2 in the 2-state model may be labeled another state in the 3-state model. It is true States 2, 3, and 4 are defined by the same parameters, but the number of data points are less as number of states increases (Table 8).

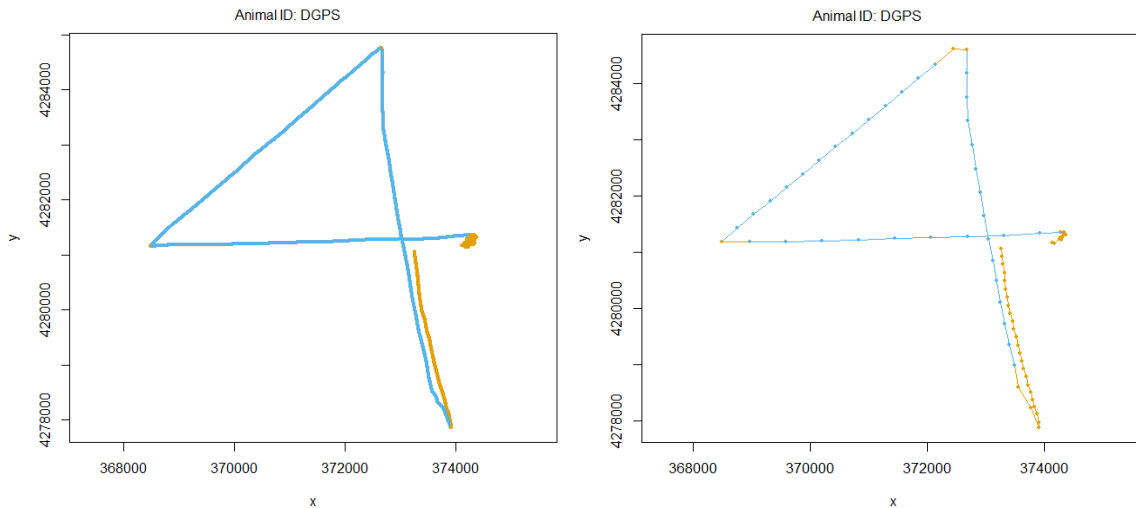


Fig. 41—Full DGPS track state encoded by a 2-state HMM. Orange and blue points represent States 1 and 2 and state parameters can be found in Table 8. X-axis is in Easting and Y-axis is in Northing.

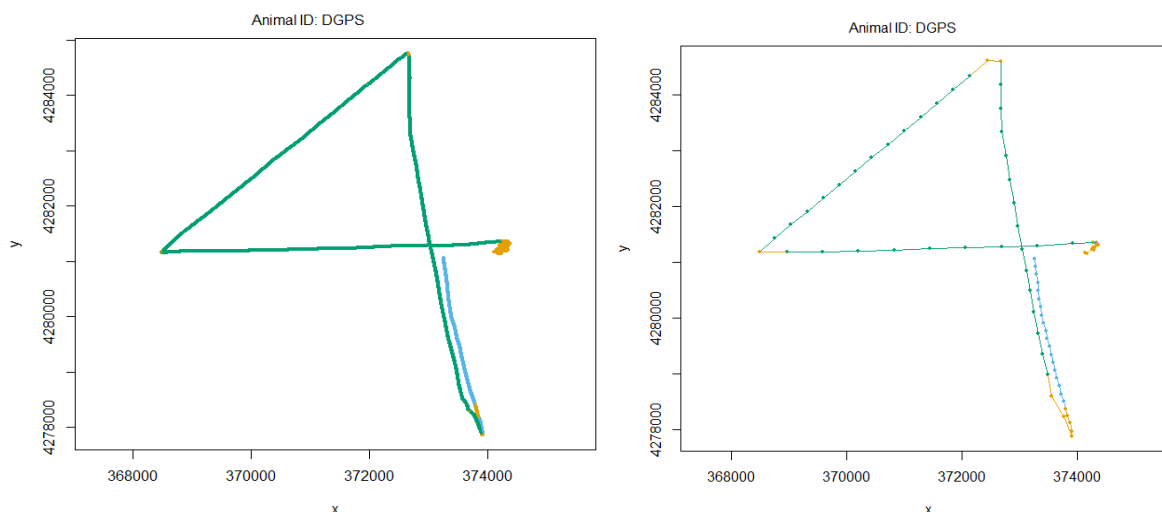


Fig. 42—Full DGPS track state encoded by a 3-state HMM. Orange, blue, and green points represent States 1, 2 and 3 and state parameters can be found in Table 8. X-axis is in Easting and Y-axis is in Northing.

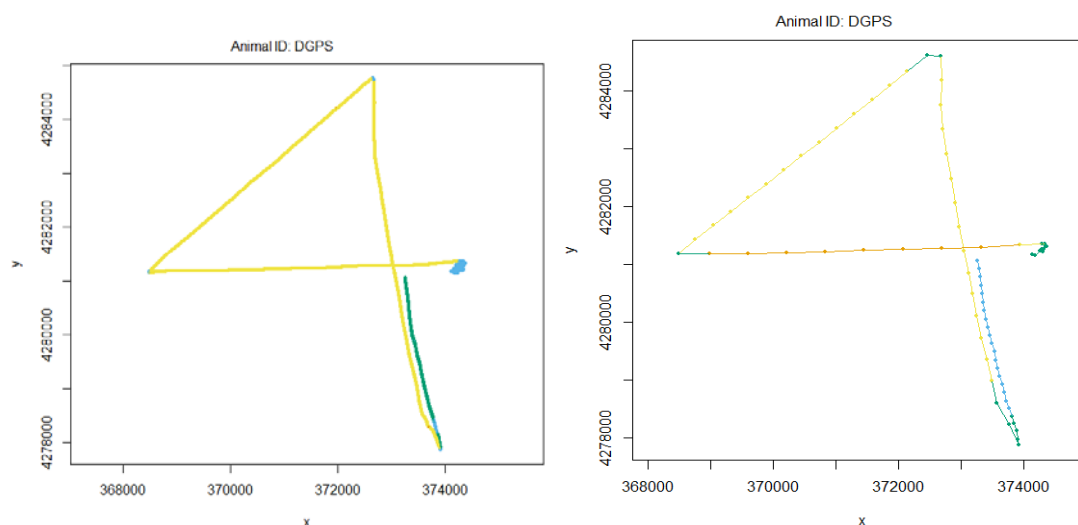


Fig. 43—Full DGPS track state encoded by a 3-state HMM. Orange, blue, green, and yellow points represent States 1, 2, 3 and 4 and state parameters can be found in Table 8. X-axis is in Easting and Y-axis is in Northing.

General knowledge of the system kinematics and desired number of states were the only two items required for the HMM to effectively decode movement behavior. As data was down sampled, state decoding was generally preserved. A down sampled, 4-state HMM was shown to be the most intuitive state decoding scheme for the vessel stuff. If all tag transmissions were captured and geo-located to less than a meter, the track would look similar to the DGPS in Fig. 40. In Section 3.2, considerable error in Argos Web locations was found. In the following section, an implementation of multi-state HMMs using a low-fidelity ArgosWeb locations is provided.

ArgosWeb reported less than half the expected number of transmissions from both tags. Of the positions reported, many coordinates were duplicates. There are 5 unique coordinates for the SPOT 258F tag and 5 unique coordinates for the SPOT 303C over Runs 2, 3 and 4. The HMM fails to fit the step size distribution because of the considerable zero-inflation. The sparsity, inaccuracy, and converge failure of

the HMM found in the Argos Web SPOT 258F and SPOT 303C data sets further question the meaningfulness of the 3-state HMM results described earlier. One cannot make predictions of marine mammals behavior in the presence of vessels, depth change or distance to coast if data from the Mid Atlantic Humpback study is as inaccurate as what was found in Section 3.2. These findings present a clear need to explore fuzzy HMMs capable of incorporating known inaccuracy and error analysis results.

Table 8—Distance and Turning Angle Parameter 95% Confidence Intervals Generated by Multi-State HMMs for DGPS Track Data

| No. of States | Sampling Rate (secs) | State 1                                         |                                                              | State 2                                          |                                                           | State 3                                            |                                                         | State 4                                         |                                                        |
|---------------|----------------------|-------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------------|----------------------------------------------------|---------------------------------------------------------|-------------------------------------------------|--------------------------------------------------------|
|               |                      | Step Size (m)                                   | Turning Angles (rads)                                        | Step Size (m)                                    | Turning Angles (rads)                                     | Step Size (m)                                      | Turning Angles (rads)                                   | Step Size (m)                                   | Turning Angles (rads)                                  |
| 2             | 1                    | $k$<br>(1.69, 1.71)<br>$\theta$<br>(0.26, 0.27) | $\mu$<br>(6.9e-3, 0.012)<br>$\kappa$<br>(162, 179)           | $k$<br>(4.89, 4.95)<br>$\theta$<br>(1.00, 1.05)  | $\mu$<br>(-4.4e-4, 7.1e4)<br>$\kappa$<br>(3.14e3, 3.15e3) | -                                                  | -                                                       | -                                               | -                                                      |
|               | 90                   | $k$<br>(123, 264)<br>$\theta$<br>(90.8, 242)    | $\mu$<br>(-2.94, 2.9)<br>$\kappa$<br>(0.08, 0.98)            | $k$<br>(290, 381)<br>$\theta$<br>(138, 216)      | $\mu$<br>(-0.011, 0.014)<br>$\kappa$<br>(336, 808)        | -                                                  | -                                                       | -                                               | -                                                      |
| 3             | 1                    | $k$<br>(1.84, 1.89)<br>$\theta$<br>(0.44, 0.49) | $\mu$<br>(-0.52, 0.27)<br>$\kappa$<br>(0.81, 2.12)           | $k$<br>(1.61, 1.62)<br>$\theta$<br>(0.04, 0.042) | $\mu$<br>(-0.01, 0.01)<br>$\kappa$<br>(386, 0.001)        | $k$<br>(4.89, 4.96)<br>$\theta$<br>(0.99, 1.04)    | $\mu$<br>(-4.6e-4, 6.2e4)<br>$\kappa$<br>(3.6e3, 3.6e3) | -                                               | -                                                      |
|               | 90                   | $k$<br>(124, 251)<br>$\theta$<br>(89.9, 222)    | $\mu$<br>(-2.72, 2.63)<br>$\kappa$<br>(0.081, 0.99)          | $k$<br>(144, 146)<br>$\theta$<br>(1.36, 2.59)    | $\mu$<br>(-0.016, 0.030)<br>$\kappa$<br>(372.9, 372.05)   | $k$<br>(412, 472)<br>$\theta$<br>(71.6, 116)       | $\mu$<br>(-0.01, 8.1e-3)<br>$\kappa$<br>(964.7, 964.8)  | -                                               | -                                                      |
| 4             | 1                    | $k$<br>(1.48, 1.57)<br>$\theta$<br>(0.01, 0.04) | $\mu$<br>(9.3e-1, 0.93)<br>$\kappa$<br>(1.0e3, 1000)         | $k$<br>(1.85, 1.90)<br>$\theta$<br>(0.44, 0.49)  | $\mu$<br>(0.018, 0.31)<br>$\kappa$<br>(78.9, 93.0)        | $k$<br>(1.615, 1.619)<br>$\theta$<br>(0.01, 0.042) | $\mu$<br>(-0.002, 2.3e-2)<br>$\kappa$<br>(481, 4.8e2)   | $k$<br>(4.89, 4.95)<br>$\theta$<br>(0.99, 1.05) | $\mu$<br>(-4.6e-4 6.2e-4)<br>$\kappa$<br>(3.6e3 3.6e3) |
|               | 90                   | $k$<br>(617, 622)<br>$\theta$<br>(2.19, 5.86)   | $\mu$<br>(-7.4e-3, 2.3e-2)<br>$\kappa$<br>(2.04e-2, 2.04e-3) | $k$<br>(144, 146)<br>$\theta$<br>(1.36, 2.59)    | $\mu$<br>(-0.02, 0.03)<br>$\kappa$<br>(371, 372)          | $k$<br>(124, 250)<br>$\theta$<br>(89.6, 221)       | $\mu$<br>(-2.74, 2.63)<br>$\kappa$<br>(0.086 0.99)      | $k$<br>(382, 399)<br>$\theta$<br>(17.9, 30.4)   | $\mu$<br>(-0.012 0.007)<br>$\kappa$<br>(857.7 8.57.8)  |

### 4.3 Forecasting Marine Mammal Satellite Tag Data

In Section 2.3.1, a UC model for marine mammal telemetry data is introduced [15,16]. Similar to what was observed in the Section 4.2 on HMMs, the ArgosWeb data is simply too small of subset to provide a meaningful UC model implementation. For the remainder of this Section, the DGPS ground truth data tracking the two marine mammal tags will be used in the UC model. If a system is developed to accurately detect and locate all marine mammal telemetry transmissions, it is assumed the UC model will forecast and interpolate similar to the DGPS ground truth data set.

In Equation 15, the unobserved component contains a seasonal component where harmonics must be defined. For each Run described in Section 3.2, step sizes and turning angles were observed over time. In both Runs 2 and 3, only two speeds and two directions occurred. Thus, it is postulated a minimum of two harmonics were needed to define the unobserved component portion of the UC model. In Run 4, a meandering behavior occurred consisting of many turns at a relatively constant speed. For Run 4, it is postulated the number of harmonics was equal to the number of turns observed in the time series.

Run 2, 3, and 4 were explored separately. To demonstrate the proficiency of the UC model's ability to forecast and interpolate missing data, random subsets of data were removed from Run 2, 3, and 4's timeseries. Prior to initialization the UC model, various smoothing techniques were explored to decide which GRW was most appropriate for each Run. Recall, the UC model assumes TVP are either RW, IRW, and DIRW. The 'irwsm' function in the CAPTAIN Toolbox used to smooth and decimate the time series. Each run had two time series that defined a behavior: turning angle and step size. The 'irwsm' function requires a noise parameter and state estimation probability which were set to 0.0001 and 0.95 respectively. With the 'irwsm', TVPs of RW, IRW, and DIRW were set for both the turning angle and step size time series (Fig. 41-44). Figure 41 shows Run 4's smoothed step size time series using the following methods: RW, IRW, DIRW, Moving Average, Savitzky-Golay, and Local Regression. Fig. 43 shows Run 4's smoothed turning angle time series using the same smoothing methods in Fig. 41.

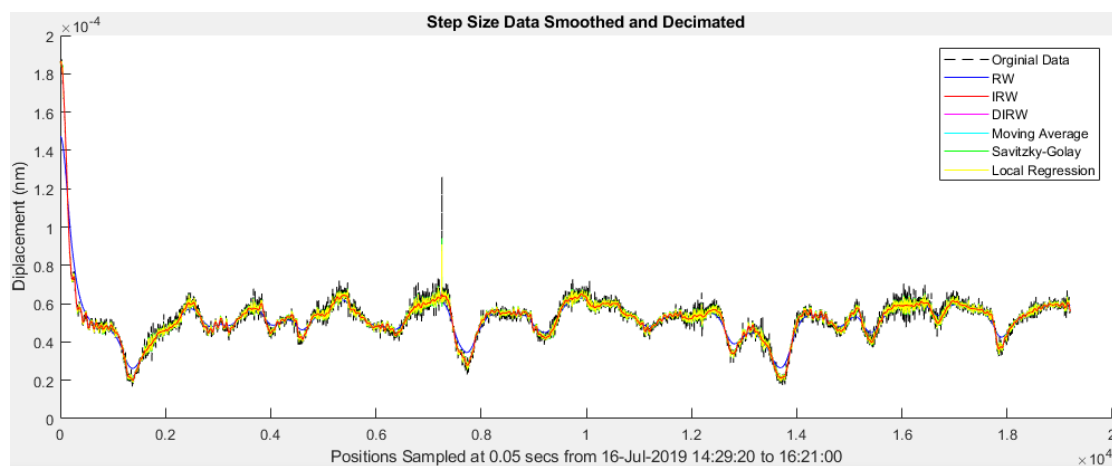


Fig. 44—Various smoothed fit methods applied to Run 2 step size DGPS data

Analysis of the residuals for each smoothing method indicated top smoothing methods for Run 4's step size time series were the Local Regression, IRW and DIRW (Fig. 42). Since the Local Regression method tends to be resistant to outliers, it is clear why the Local Regression was a best fit for Run 4's step size data: a large outlier between samples 6000 and 8000 (Fig. 41). However, when smoothing the turning angles for Run 4, the residual error was smallest for the RW and DIRW method (Fig. 44). RW, IRW,

DIRW, Moving Average, Savitzky-Golay, and Local Regression smoothing methods were applied to Runs 2 and 3 in a similar fashion. The DIRW and RW smoothing method had the lowest residuals across all run's step sizes and turning angles. Thus, TVP was set to either '0' indicating RW or '2' indicating DIRW during optimization of the UC model [15,16].

The '*dhropt*' estimates the Dynamic Harmonic Regression (DHR) model's hyper-parameter. Recall the DHR designates a UC model that includes a seasonal or cyclical component and the hyper parameters define the statistical properties of the TVP. The only parameters altered in the '*dhropt*' function number of harmonics (e.g. seasons or cycles) and the order of the AR. AR orders of 1 to 50 were explored for all models.

For Run 2, two harmonics were assumed for the step size and turning angle time series (Fig. 45-48). TVP was set to a RW. A subset of data when the vessel was traveling at 3kts south of the Goniometer/RXG-134 receiving equipment was removed for interpolation: samples 20000 through 30000 or 500 seconds (8.3 mins). Another subset of data was removed for forecasting purposes when the vessel increased speed to 8 kts and turned in the opposite direction: samples 65000 through 71567 or 325 seconds (5.47 mins). Once the '*dhropt*' estimates the DHR model's hyper-parameters, the '*dhr*' function estimates the DHR model and provides smoothed estimates of the time series. The same parameters used in the step size '*dhropt*' function proved efficient for Run 2's turning angles. The DHR interpolated the missing step size and turning angle data at 3kts and 180 degrees as expected (Fig. 46 and 48). The DHR forecasted step size to decrease slightly (reduce speed) and increase turning angle (prepare to turn) (Fig. 48).

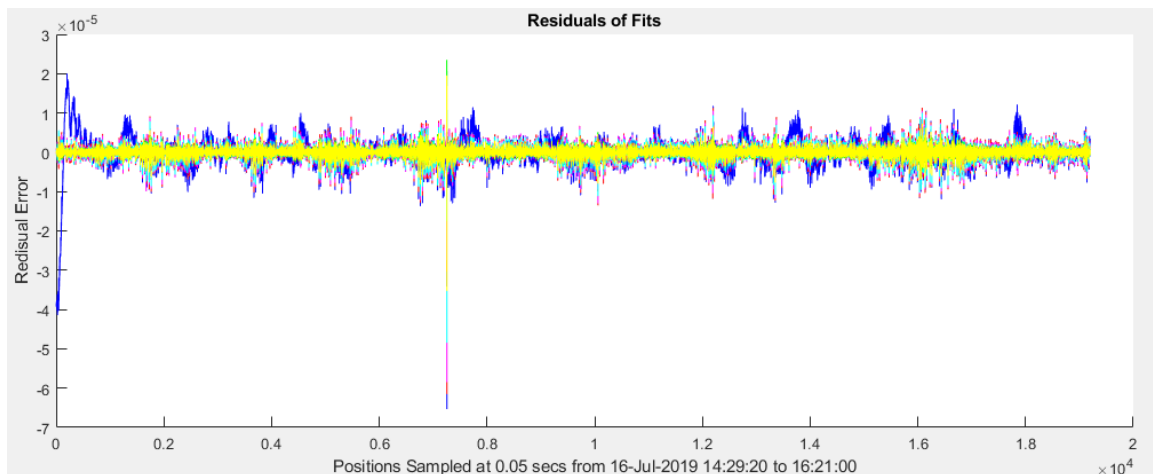


Fig. 45—Residuals of smoothed fits applied to Run 2 step size DGPS data, where colors correspond to methods in Fig. 41

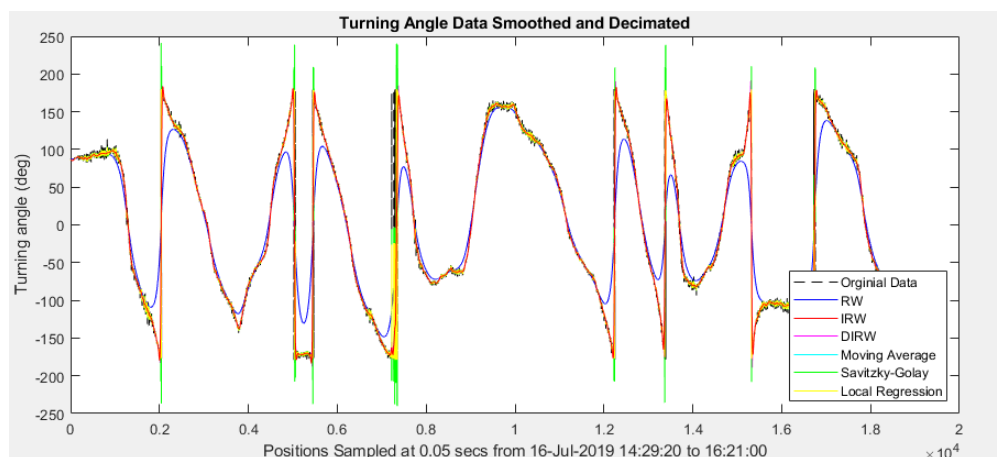


Fig. 46—Various smoothed fit methods applied to Run 2 turning angle DGPS data

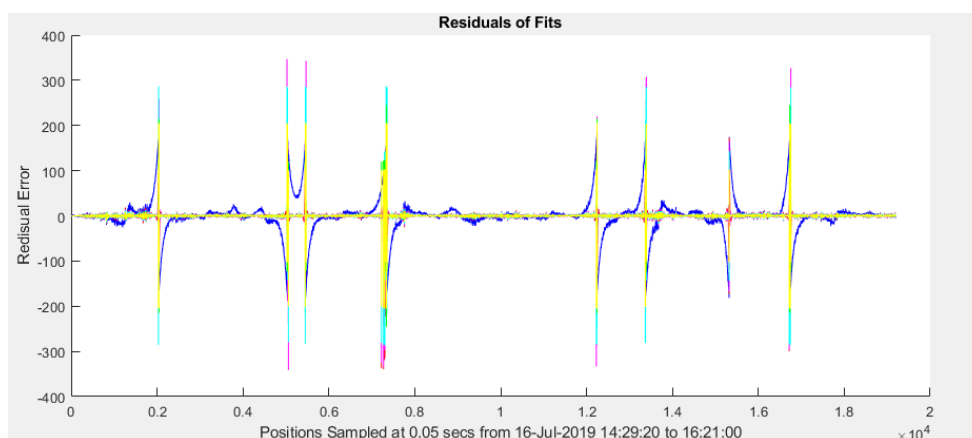


Fig. 47—Residuals of smoothed fits applied to Run 2 turning angle DGPS data, where colors correspond to methods in Fig. 43

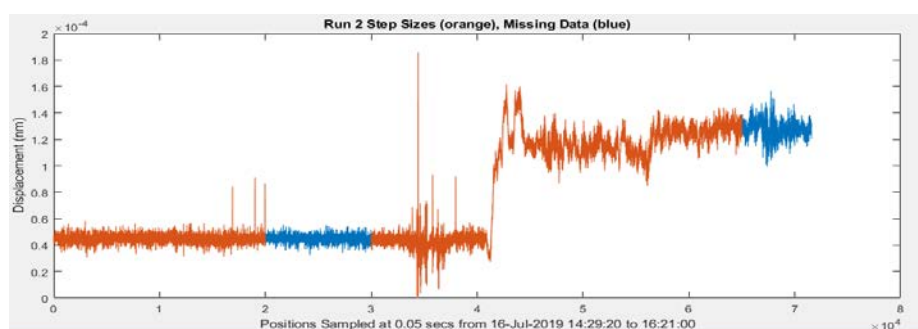


Fig. 48—Step size time series for Run 2. Blue data points denote missing data where DHR will interpolate and forecast.

In Run 3, the vessel was traveling towards the receiver at 8kts and abruptly made a turn away from shore at 13kts (Fig. 49 and 50). Samples 15000 through 20000 or 250 seconds (4.2 mins) were removed for interpolation. The interpolation in Run 3 performed as expected, predicting the vessel to have average step sizes at 8kts and direction 130 degrees south as expected. Samples 40000 and onward were removed for forecasting. The forecasting results underestimated the actual step size and turning angles (Figs. 50

and 52). Like with Run 2, two harmonics were explored for both step size and turning angle UC model. Various AR orders were explored. Increasing AR order, made the underestimate of the forecast more severe. Since the magnitude of speed and direction was so abrupt compared to Run 2, the AR should place less dependency on previous observations and by decreasing the AR order. This startled behavior should be dubbed unusual, similar to an outlier, and including the observation in the AR order skews the results.

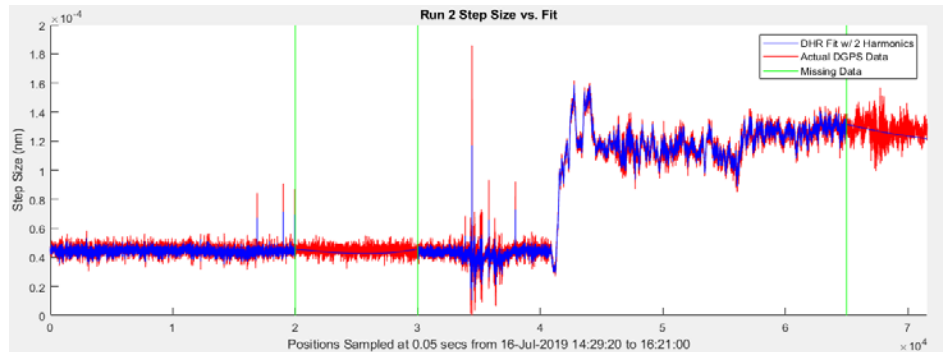


Fig. 49—DHR fit (blue) to actual Run 2 step size data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 20000 through 30000 and 65000 through 71567.

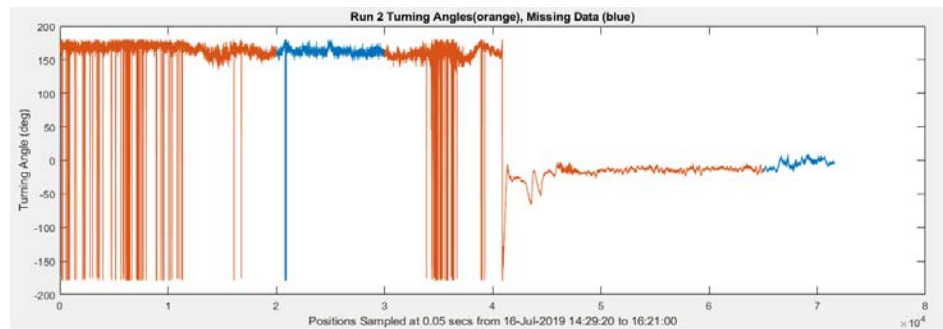


Fig. 50—Turning angle time series for Run 2. Blue data points denote missing data where DHR will interpolate and forecast.

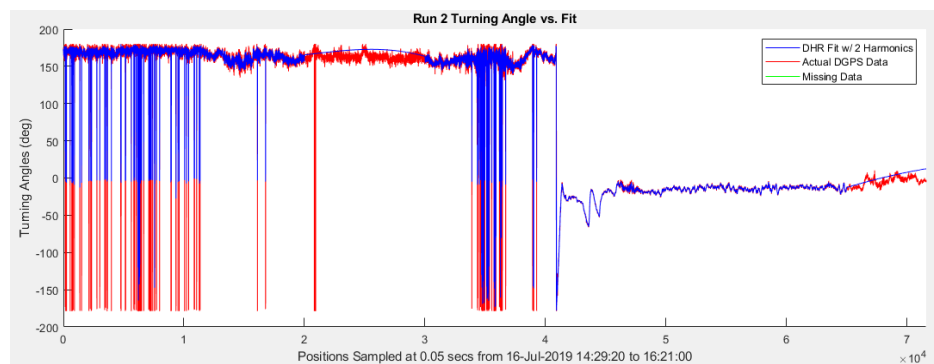


Fig. 51—DHR fit (blue) to actual Run 2 turning angle data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 20000 through 30000 and 65000 through 71567

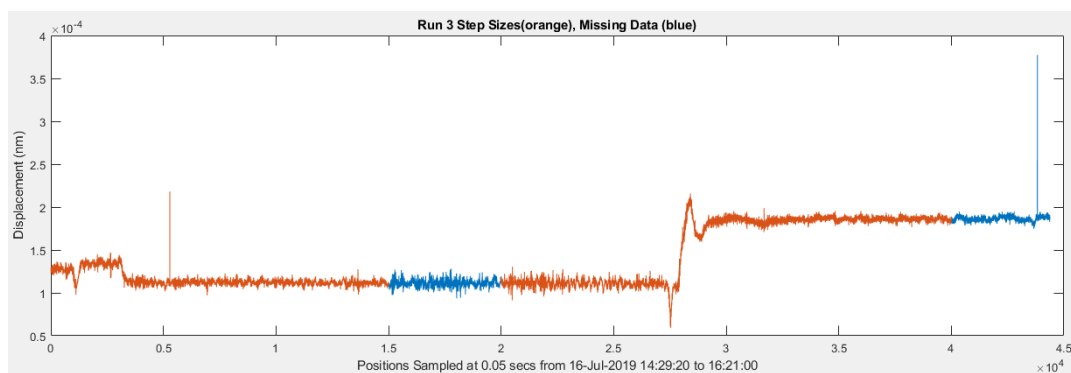


Fig. 52—Step size time series for Run 3. Blue data points denote missing data where DHR will interpolate and forecast.

For Run 4, the vessel operators were instructed to meander randomly between 3 and 5 kts. Samples 8000 and 9800 or 60 secs (1.5 min) were removed for interpolation (Fig. 53 and 56). There exists an outlier in both the step size time series for Run 4 (Fig. 53–55). Harmonics were first determined by the number of “loops” or circles made by the vessel in Run 4 (Figure 31). Harmonics of 9 through 20 were explored. An AR order of 5 or higher produced the most accurate interpolated track. In the step size time series, 10 harmonics was slightly better than 16 harmonics even though 16 harmonics captures the phase of the actual step size data (Figs. 54 and 55). However, the difference between the two fits is not substantial, error on the order of  $10^{-8}$ . For Run 4’s turning angles, harmonics of 9 and 10 proved to be the best fits (Figs. 57 and 58). Each fit is in phase and accurately captures the change in direction of the vessel. Similar to what was seen in Run 4’s step size distribution, the residual error between Figs. 54 and 55 fits is on the order of  $10^{-8}$ .



Fig. 53—DHR fit (blue) to actual Run 3 step size data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 15000 through 20000 and 40000 through 45100.

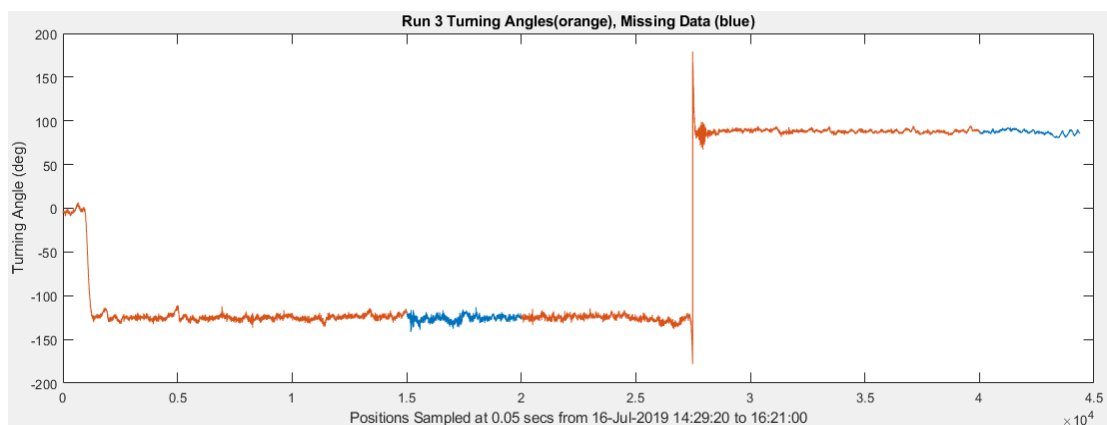


Fig. 54—Turning angle time series for Run 3. Blue data points denote missing data where DHR will interpolate and forecast.



Fig. 55—DHR fit (blue) to actual Run 3 turning angle data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 15000 through 20000 and 40000 through 45100.

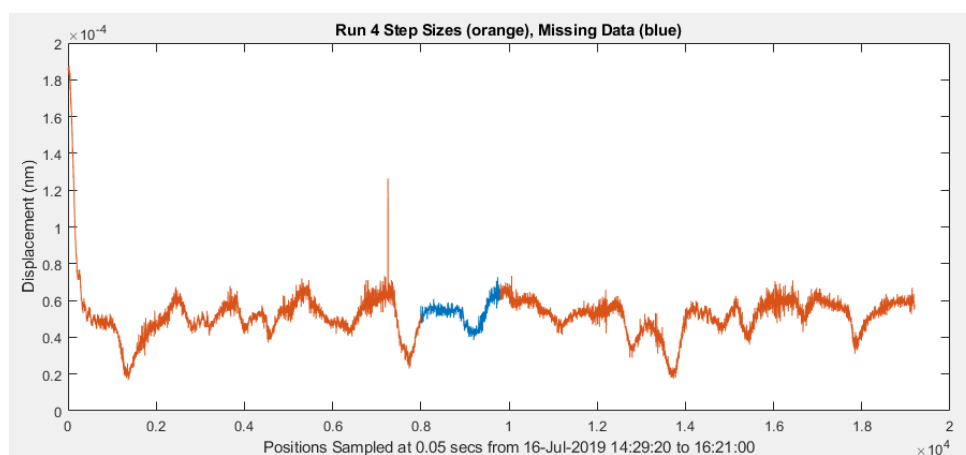


Fig. 56—Step size time series for Run 3. Blue data points denote missing data where DHR will interpolate and forecast.

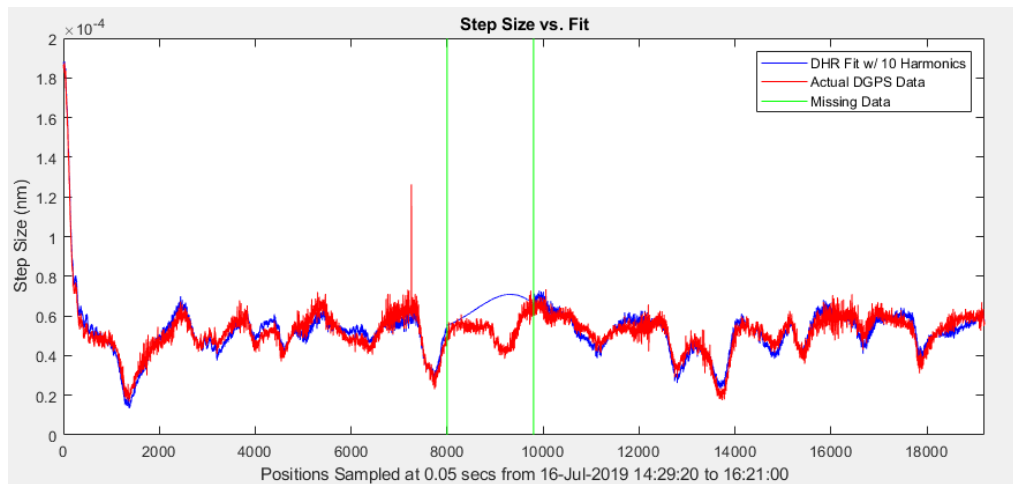


Fig. 57—DHR fit (blue) to actual Run 4 step size data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 8000 and 8900. Ten harmonics were used in the UC model.

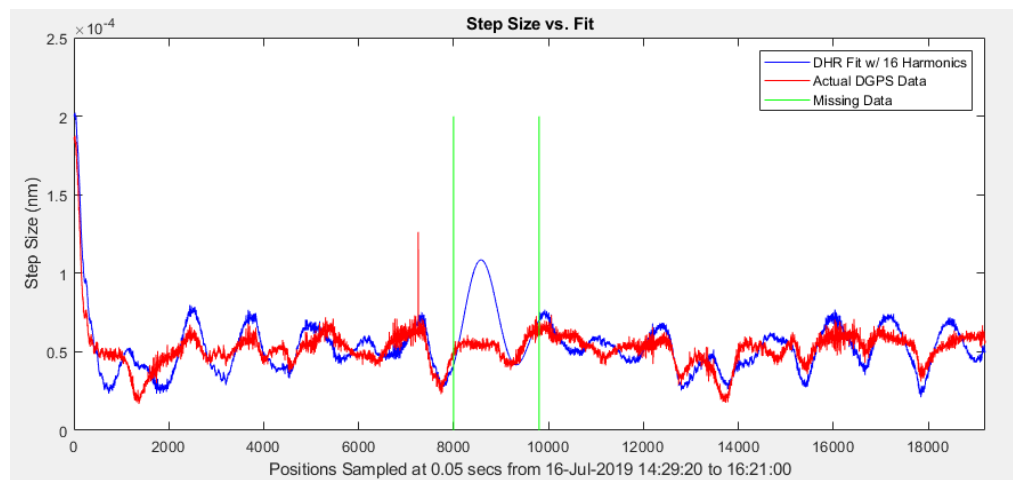


Fig. 58—DHR fit (blue) to actual Run 4 step size data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 8000 and 8900. Nine harmonics were used in the UC model.

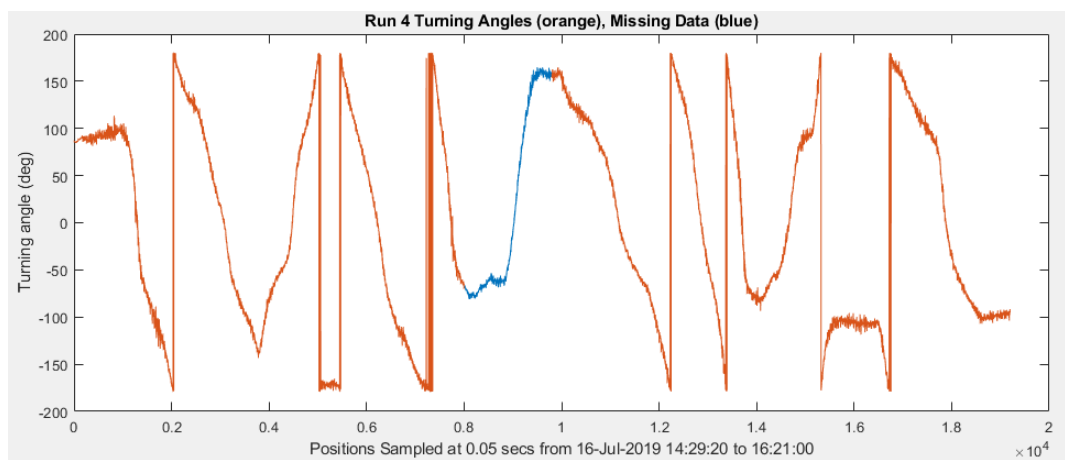


Fig. 59—Turning angle time series for Run 4. Blue data points denote missing data where DHR will interpolate and forecast.

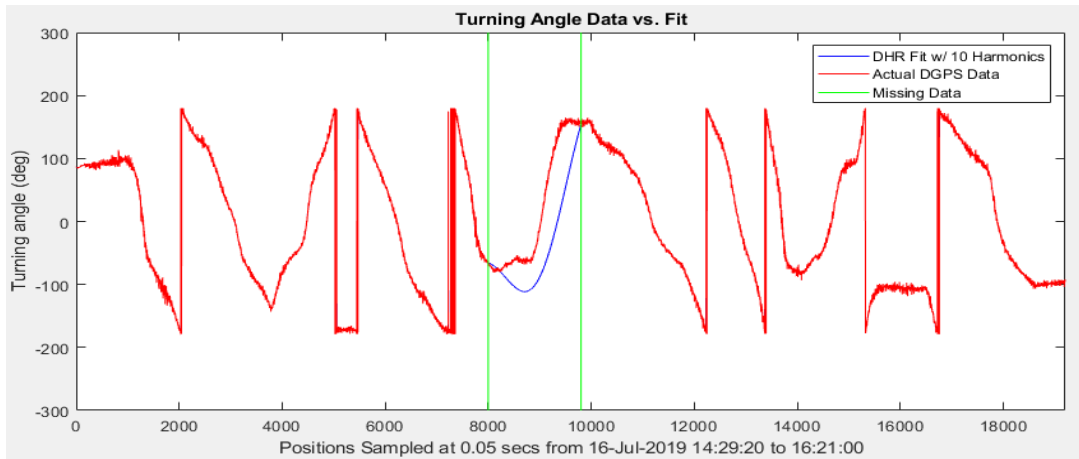


Fig. 60—DHR fit (blue) to actual Run 4 turning angle data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 8000 and 8900. Ten harmonics were used in the UC model.

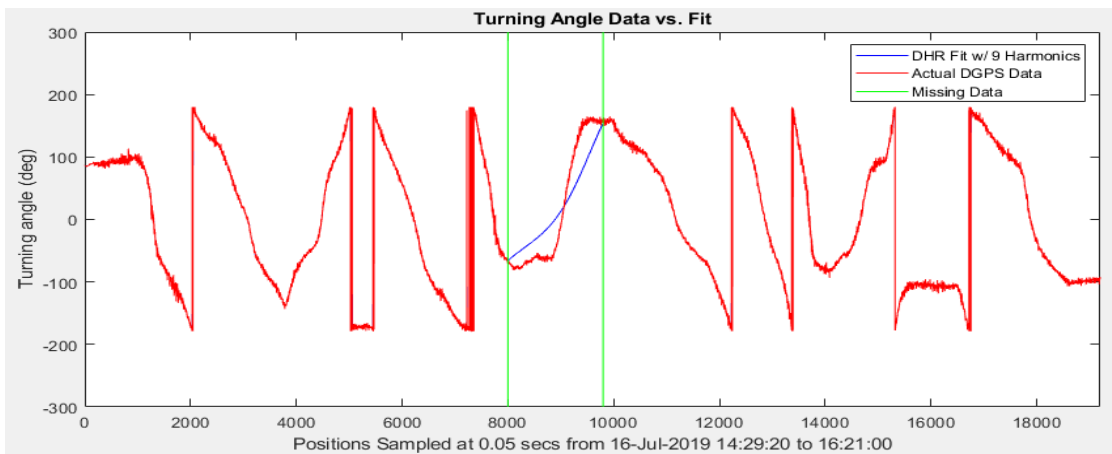


Fig. 61—DHR fit (blue) to actual Run 4 turning data (red). Missing data sections where the DHR interpolated and forecasted data lie between samples 8000 and 8900. Nine harmonics were used in the UC model.

Marine mammal telemetry data may be forecasted and interpolated with minimum prior knowledge of the system. Run 4, demonstrates an encamped state where a marine mammal is in a confined area making frequent turns, similar to what is seen when humpbacks feed. In this scenario more harmonics are required. In Runs 2 and 3 where a marine mammal is simulated to be passing through, traveling, or escaping, it is reasonable to assume harmonics should be low since marine mammals transiting speed is small range and paths are generally straight. The fits for each behavior can be adjusted by the assumed TVP, the number of harmonics and the order of the AR. Assuming a RW for the TVPs realized a more accurate interpolation and forecasting of the data. More harmonics are expected in encamped behaviors like feeding or breeding than linear, transiting behaviors. The AR alters how much weight should be given to past observations. If an unusual behavior occurred, a lower AR is more resilient to anomalies in marine mammal tag data.

## **Conclusions**

While Argos-based marine mammal tags are ideal for its breadth of coverage, researchers and the U.S. Navy must be aware of the shortcomings of marine mammal tag data. The Argos satellite receiving and processing methods produce location errors on a kilometer scale. Locations are not only inaccurate, but also untimely; it takes up to twenty minutes for data to be posted on Argos Web. A U.S. Navy marine mammal detection and prediction system cannot be based on inaccuracies on this magnitude. Either the Argos data processing methods should be investigated further or the U.S. Navy must devise its own marine mammal tag receiving capabilities.

Marine mammal ecologists and biologists will continue to tag species for short and long-term behavioral analysis and habitat range modeling. At the 2017 Biannual Society of Marine Mammals (SMM) Conference in Halifax, Nova Scotia, nearly 100 of researchers presented findings based on tag data. Tagging is has become so popular the conference hosts a workshop taught by St. Andrews University researchers on tag data processing methods. Tagging will not cease among the marine mammal community, thus the U.S. Navy should capitalize on the thousands of actively deployed marine mammal tags in the battlespace environment.

Tag transmission capture can be accomplished with the use of cost-effective SDR radios. Tag transmissions can be identified and timestamped for directional finding through MPs. Existing direction-finding equipment on U.S. Navy vessels should be tuned to the Argos frequency to intercept tag transmission and geo locate their positons. Existing U.S. Navy receiving systems have more advanced capabilities than the RXG-134 Goniometer receiving system, thus purchasing a RXG-134 Goniometer is unnecessary.

The U.S. Navy operates in ocean and is on a 24/7 watch. The likelihood of the Navy encountering a marine mammal is high. The U.S. Navy should leverage existing receiving systems to collect marine mammal transmissions. As marine mammal detections are accumulated, behavioral classification and forecasting algorithms, such as the HMM and UC model, should applied and use for decision-making. The HMM is a capable of including covariate data such as sea surface temperature, sea state, depth, and other oceanographic variables. As marine mammal tracks are constructed, the HMM should incorporate these covariates because of their known effect species (e.g. some species prefer cooler temperatures than others do). Two important covariates for the U.S. Navy is vessel presence and active sonar use. Collecting marine mammal detections and maintaining tracks would allow the U.S. Navy to make real-time decisions of whether an exercise is likely to harm nearby marine mammals. The HMM would assist the U.S. Navy in identifying behaviors in tracks and trends between behavior and naval activities. These trends can only be realized with accurate and timely marine mammal detections.

Open-source marine mammal databases, such as ATN, locations from Argos Web, and directions provided by CLS Goniometer receiving system should be treated as presence-only marine mammal detections. The inaccuracies of Argos-based marine mammal tags are not suitable for classifying and predicting marine mammal movement. If there existed GPS-based tags, similar to the DGPS used in Section 3.2, classification and forecasting algorithms can be applied. In the event gaps of data are missing from the marine mammal tag time series, the UC Model used in Section 4.3 is capable of accurately interpolating the missing data given a reasonable set of harmonics and trend values. Because tags capable of the precision of DGPS receiver do not exist, fuzzy HMM and UC models should be explored furthered.

The PF demonstrates the feasibility to incorporate value marine mammal expert knowledge, such as species maximum speeds, and various data source in order to produce a reasonable track trajectory. Other data sources, such as passive acoustics and visual sightings, could act as prior knowledge within the PF as opposed to the Goniometer direction angles. Passive acoustic buoys developed by Woods Hole is a

currently available data source that should be leveraged by the U.S. Navy. These buoys automatically detect large whale species calls in dense vessel traffic areas like the New York Bight. Dr. Helen Bailey of Maryland's Center for Environmental Science recently deployed a Woods Hole buoy in order to assess whale activity in a proposed wind farm area. This proposed wind farm area is located off the coast of Ocean City, MD.

Marine mammal detection is not limited to passive acoustics, visual/aerial surveys, and tagging. At the Biannual SMM Conference, many New Technology poster, lecture, and workshop sessions are presented. Researchers have become creative in their studies: tags come equipped with video cameras and sensors to sample chlorophyll levels in the water, drones estimate marine mammal body lengths, whales are located in satellite imagery, and sail gliders detect whale calls. Some researchers have attempted to supplement the low marine mammal tag detection rate by establishing wireless sensor networks such as acoustic arrays or proposing deployment of small low earth orbit satellites. The U.S. Navy has hydrophone arrays capable of detecting marine mammals similar to these networks: the M3R system. If more of these marine mammal sensor networks could be installed on U.S. Navy ranges, time and money spent searching for marine mammals in flight or on the bridge will surely be reduced.

Many marine mammal detection methods exist, however few have been validated for U.S. Navy use. Marine mammal tag data is just one of the many sources that should be assessed for quality and accuracy prior to the development of an automatic marine mammal detection system.

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## APPENDIX A

Table A1—Argos System Equipment Providers for Animal Tracking as of July 2018

| Manufacturer                                                                        | Applications                                                                        | Address & Website                                                                                                                                    |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
|    |    | The Old Courts, Worgret Road,<br>Wareham, BH20 4PL,<br>UNITED KINGDOM<br><br><a href="http://www.biotrack.co.uk">www.biotrack.co.uk</a>              |
|    |    | 8-2-25, Nankou-Higashi,<br>Suminoe-ku,<br>Osaka 559-0031<br>JAPAN<br><br><a href="http://www.core.co.jp">www.core.co.jp</a>                          |
|    |    | 3261 Imjin Road<br>Marina, CA 93933<br>USA<br><br><a href="http://www.desertstar.com">www.desertstar.com</a>                                         |
|   |    | 15-73 Leningradskoe Shosse<br>125171 Moscow<br>RUSSIA<br><br>Email: <a href="mailto:a.salman@es-pas.com">a.salman@es-pas.com</a>                     |
|  |  | 2521 Schieffelin Road<br>Suite 136<br>Apex, NC 27502<br>USA<br><br><a href="http://www.geotrakinc.com">www.geotrakinc.com</a>                        |
|  |  | PO Box 698<br>Essex, MT 59916<br>USA<br><br><a href="http://www.HawkOwl.com">www.HawkOwl.com</a>                                                     |
|  |  | 115 Pony Drive<br>Newmarket ON L3Y 7B5<br>CANADA<br><br><a href="http://www.lotek.com">www.lotek.com</a>                                             |
|  |  | C/ San Marcos n°100<br>14520 Fernan Nuñez (Córdoba)<br>SPAIN<br><br><a href="http://www.microsensory.com">www.microsensory.com</a>                   |
|  |  | 8835 Columbia 100 Parkway<br>Suites K & L Columbia MD 21045<br>USA<br><br><a href="http://www.microwavetelemetry.com">www.microwavetelemetry.com</a> |

|                                                                                                                                        |                                                                                     |                                                                                                                                                                       |
|----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <br>Nomad Science Inc.                                |    | R&D Center<br>754-1 Koyurugi Samukawa-machi<br>Kanagawa 253-0102<br>JAPAN<br><br><a href="http://www.nomadsci.com">www.nomadsci.com</a>                               |
| <br>NORTH STAR<br>Science and Technology              |    | PO Box 438<br>King George VA 22485<br>USA<br><br><a href="http://www.northstarst.com">www.northstarst.com</a>                                                         |
|                                                       |    | Private Bag 1403<br>Havelock North 4230<br>NEW ZEALAND<br><br><a href="http://www.sirtrack.com">www.sirtrack.com</a>                                                  |
| <br>Sea Mammal<br>Research Unit<br>Instrumentation    |    | Gatty Marine Laboratory<br>University of St-Andrews KY16 8LB<br>St. Andrews, Fife<br>SCOTLAND<br><br><a href="http://www.smru.st-and.ac.uk">www.smru.st-and.ac.uk</a> |
| <br>SEXTANT<br>technology ltd                         |    | 116 Wilton Rd<br>Wellington 6012<br>NEW ZEALAND<br><br><a href="http://www.s-t.co.nz">www.s-t.co.nz</a>                                                               |
| <br>TechnoSmArt<br>GPS TRACKING SYSTEMS FOR ANIMALS |  | via Antonio Signorini 20<br>00134, Rome<br>ITALY<br><br><a href="http://www.technosmart.eu">www.technosmart.eu</a>                                                    |
| <br>TELONICS                                        |  | 932 East Impala Avenue<br>Mesa AZ 85204<br>USA<br><br><a href="http://www.telonics.com">www.telonics.com</a>                                                          |
| <br>WILDLIFE<br>COMPUTERS                           |  | 8345 154th Avenue NE Redmond<br>WA 98052<br>USA<br><br><a href="http://www.wildlifecomputers.com">www.wildlifecomputers.com</a>                                       |
| <br>XERIUS<br>Think, design & create                |  | ZA Le Cassé II<br>4, rue Jean Monnet<br>31240 St Jean<br>FRANCE<br><br><a href="http://www.xeriustracking.fr">www.xeriustracking.fr</a>                               |

**APPENDIX B**

# SPOT TAG PRODUCT SHEET:

## SPOT 303

**OVERVIEW**

When at the surface, SPOT tags send out short transmissions to the Argos satellite system. Consecutive transmissions received in a single satellite pass are used to calculate the location of the transmitter. Locations are available online in near real time with accuracies as good as 250 m.

**Attachment Options:** Glue on, fin mount, flipper mount, float mount, AUV mount, towed, and anchored.

**Size Options:** Ranging from 30 grams to 390 grams and in over 50 shapes for marine animal, float, and UAV applications.

**Complete Flexibility in Argos Uplink Schedule**

The SPOT Argos uplink schedule is completely user-customizable. The researcher has the power to decide how many transmissions to attempt each hour of the day. This allows the temporal resolution to be increased during parts of the day or year that are of greatest interest. Transmissions can be suspended and battery power saved when Argos satellite coverage is poor or when animal locations are known.

**The Portal Advantage**

SPOT tags are supported by the Wildlife Computers Data Portal, a collection of data management tools and services. Developed specifically for the display and investigation of data from Wildlife Computers tags, the data portal streamlines the processes of acquiring, preserving, viewing, and sharing SPOT location and temperature data.

**Consulting Services**

Our consultation team—which includes on-staff biologists—works to understand your project goals including what data you need, what animal you are researching, environment, and more. The team uses the knowledge gathered over the last 30 years on best practices, techniques, and procedures to make recommendations for getting the data you need to meet your objectives.

**Power Savings**

SPOT tags incorporate a battery-saving transmission regime to help prolong tag life while optimizing data reception. Short, three-byte messages are sent whenever data is not in the queue. Sending shorter messages takes less power and prolongs tag life.

## Pinger

The SPOT includes a pinger for radio tracking. Animals can be located and assets recovered with the use of a directional antenna and receiver.

## Specialized Shapes

SPOT tags are available in many shapes to suit a variety of taxa. Wildlife Computers partnered with the research community to refine each configuration for its intended application. The sensors and antenna placement, attachment mechanism, abrasion protection, size, weight, and hydrodynamics of each shape have been carefully considered and specialized to optimize performance, maximize retention, and minimize animal impact.

## Value-added Extras

Wildlife Computers not only provides tracking technology but also mounting equipment and best practice instructions for proper tag attachment. Attachment gear is available for epoxy bonding, fin and flipper bolting, subdermal anchoring, and tethering instrumentation with a connected float.

## DATA PRODUCTS

Data products that can be transmitted: Argos Doppler Locations, Percent-Dry Timelines, and Time-at-Temperature Histograms

Below are the general physical specifications of SPOT tags:

|                                 |                                                                    |
|---------------------------------|--------------------------------------------------------------------|
| Pressure rating                 | 2000 m for most shapes                                             |
| Operating frequency             | 401.678 MHz                                                        |
| Sensors                         | Temperature, Wet/Dry                                               |
| Temperature                     | Range: -40° C to 60° C / Resolution: 0.05° C / Accuracy: +/-0.1° C |
| Conductivity operational limits | 0.1 to 5 S/m                                                       |
| Communication                   | Via USB port using Wildlife Computers USB communications cable     |
|                                 |                                                                    |

## APPENDIX C

# SPOT TAG PRODUCT SHEET: SPOT 258



### OVERVIEW

When at the surface, SPOT tags send out short transmissions to the Argos satellite system. Consecutive transmissions received in a single satellite pass are used to calculate the location of the transmitter. Locations are available online in near real time with accuracies as good as 250 m.

**Attachment Options:** Glue on, fin mount, flipper mount, float mount, AUV mount, towed, and anchored.

**Size Options:** Ranging from 30 grams to 390 grams and in over 50 shapes for marine animal, float, and UAV applications.

### Complete Flexibility in Argos Uplink Schedule

The SPOT Argos uplink schedule is completely user-customizable. The researcher has the power to decide how many transmissions to attempt each hour of the day. This allows the temporal resolution to be increased during parts of the day or year that are of greatest interest. Transmissions can be suspended and battery power saved when Argos satellite coverage is poor or when animal locations are known.

### The Portal Advantage

SPOT tags are supported by the Wildlife Computers Data Portal, a collection of data management tools and services. Developed specifically for the display and investigation of data from Wildlife Computers tags, the data portal streamlines the processes of acquiring, preserving, viewing, and sharing SPOT location and temperature data.

### Consulting Service

Our consultation team—which includes on-staff biologists—works to understand your project goals including what data you need, what animal you are researching, environment, and more. The team uses the knowledge gathered over the last 30 years on best practices, techniques, and procedures to make recommendations for getting the data you need to meet your objectives. Wildlife Computers not only provides tracking technology but also mounting equipment and best practice instructions for proper tag attachment. Attachment gear is available for epoxy bonding, fin and flipper bolting, subdermal anchoring, and tethering instrumentation with a connected float.

### Power Saving

Wildlife Computers not only provides tracking technology but also mounting equipment and best practice instructions for proper tag attachment. Attachment gear is available for epoxy bonding, fin and flipper bolting, subdermal anchoring, and tethering instrumentation with a connected float

SPOT tags incorporate a battery-saving transmission regime to help prolong tag life while optimizing data reception. Short, three-byte messages are sent whenever data is not in the queue. Sending shorter messages takes less power and prolongs tag life.

### Pinger

The SPOT includes a pinger for radio tracking. Animals can be located and assets recovered with the use of a directional antenna and receiver.

### Specialized Shapes

SPOT tags are available in many shapes to suit a variety of taxa. Wildlife Computers partnered with the research community to refine each configuration for its intended application. The sensors and antenna placement, attachment mechanism, abrasion protection, size, weight, and hydrodynamics of each shape have been carefully considered and specialized to optimize performance, maximize retention, and minimize animal impact.

### Value-added Extras

Wildlife Computers not only provides tracking technology but also mounting equipment and best practice instructions for proper tag attachment. Attachment gear is available for epoxy bonding, fin and flipper bolting, subdermal anchoring, and tethering instrumentation with a connected float.

### DATA PRODUCTS

Data products that can be transmitted: Argos Doppler Locations, Percent-Dry Timelines, and Time-at-Temperature Histograms

Below are the general physical specifications of SPOT tags:

|                                 |                                                                    |
|---------------------------------|--------------------------------------------------------------------|
| Pressure rating                 | 2000 m for most shapes                                             |
| Operating frequency             | 401.678 MHz                                                        |
| Sensors                         | Temperature, Wet/Dry                                               |
| Temperature                     | Range: -40° C to 60° C / Resolution: 0.05° C / Accuracy: +/-0.1° C |
| Conductivity operational limits | 0.1 to 5 S/m                                                       |
| Communication                   | Via USB port using Wildlife Computers USB communications cable     |

## APPENDIX D

Table D1—‘Run #1’ Instructions

| Starting Point                                                                               | COMEX                               | During Run                                                                                                                                    | FINEX                                           |
|----------------------------------------------------------------------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|
| <b>TV (yellow):</b><br>4 nm from<br>goniometer.<br>Goniometer<br>bearing 270 T.<br>Hdg 270 T | TV steer ~270 T<br>@ 3 kts (column) | After 2.0 nm. TV turns around<br>and follows same path (bearing<br>270 T from Goniometer) back to<br>starting point. Increase spd to 8<br>kts | TV stops when back at<br>initial starting point |



Fig. D1—RUN #1 Objective: Demonstration of tracking performance for approaching animal tag beacons. Large marine mammals (e.g. humpbacks) are known to travel at speeds of 3 to 8 kts. Data collection traveling marine mammal behavior characterization.

Table D2—‘Run #2’ Instructions

| Starting Point                                                                  | COMEX                                        | During Run                                                                                            | FINEX                                                 |
|---------------------------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------------------------------------------------------|-------------------------------------------------------|
| <b>TV (yellow):</b><br>4 nm from<br>goniometer.<br>Goniometer<br>bearing 030 T. | TV steer ~180 T<br>@ 3 kts (line<br>abreast) | After 4 nm. TV turns around and follows<br>same path back to starting point. Increase<br>spd to 8 kts | TV stops<br>when back at<br>initial starting<br>point |

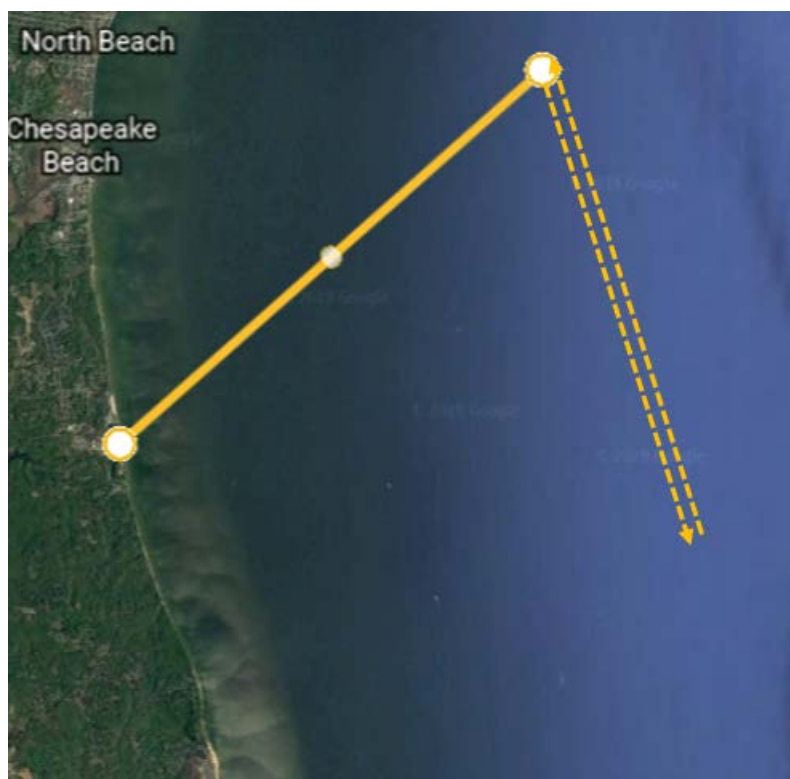


Fig. D2—RUN #3 Objective: Demonstration of tracking performance for animal tag beacons increasing traveling speed. Maximum speeds for large marine mammals (e.g. humpbacks) have been recorded at 13 kts. Data collection startled traveling marine mammal behavior characterization.

Table D3—‘Run #3’ Instructions

| Starting Point                                                                  | COMEX                     | During Run                                                                   | FINEX                                           |
|---------------------------------------------------------------------------------|---------------------------|------------------------------------------------------------------------------|-------------------------------------------------|
| <b>TV (yellow):</b><br>4 nm from<br>goniometer.<br>Goniometer<br>bearing 030 T. | TV steer 030 T<br>@ 3 kts | After 3 nm. TV turns around,<br>steering at 270 T. Increase spd to 13<br>kts | TV stops when back at<br>initial starting point |

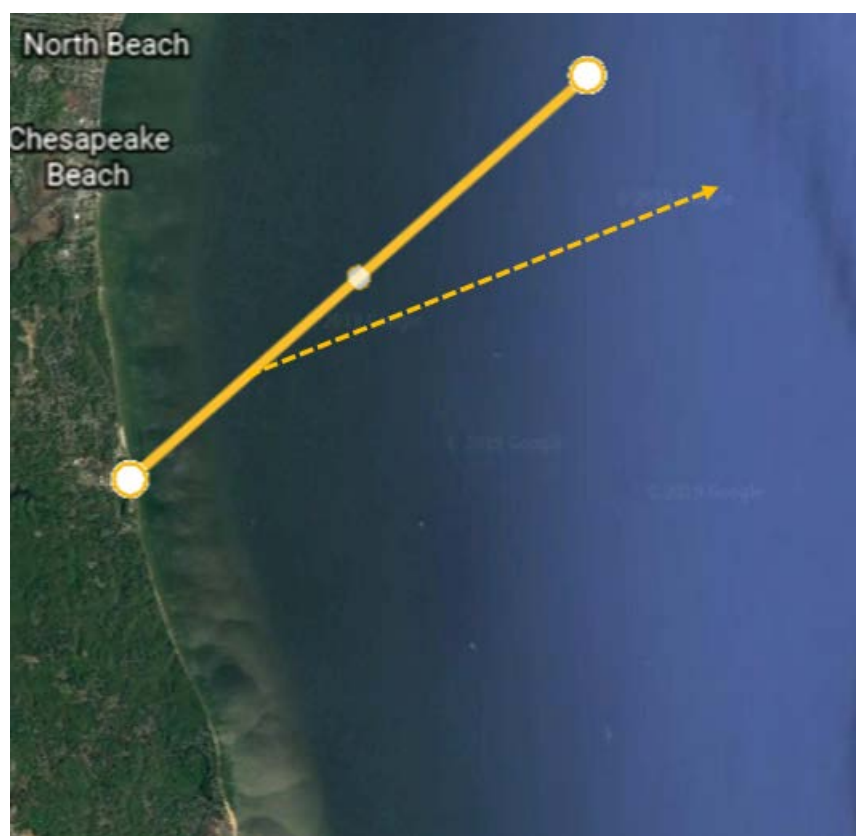


Fig. D3—RUN #4 Objective: Demonstration of tracking performance for animal tag beacons in encamped state. Data collection for feeding, breeding, and other encamped marine mammal behavior characterization.

Table D4—‘Run #4’ Instructions

| Starting Point                                                                             | COMEX                                                          | During Run                                                                                                                               | FINEX                |
|--------------------------------------------------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| <b>TV1 (red):</b><br>4 nm from<br>goniometer.<br>Goniometer<br>bearing 270 T.<br>Hdg 270 T | TV travels creates<br>a counter<br>clockwise circle at<br>3 kt | TV circles randomly for 15 mins between<br>240 T and 290 T maintain 3 nm distance<br>from goniometer. Speed kept between 3<br>and 5 kts. | TV stops at 15 mins. |



Fig. D4—RUN #4 Objective: Demonstration of tracking performance for animal tag beacons in encamped state. Data collection for feeding, breeding, and other encamped marine mammal behavior characterization.