Evaluating Electronic Methods of Fisheries Monitoring, Control, and Surveillance

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Glossary of Terms

AIS: Automatic identification system is a satellite-based fisheries surveillance program that can provide consistent information on a vessel’s position and activity. Used in areas beyond national jurisdiction (i.e. outside of exclusive economic zones).

CBA: Cost benefit analysis is a systematic approach to determining the strength and weakness of various options to calculate if the benefits outweigh the costs (David, et al. 2013).

CCTV: Closed-circuit television, i.e. video surveillance. Video cameras are used to send a signal to a specific location, on a limited set of monitors (Dempsey 2008).

Discards: Fish that are caught but are not retained on the fishing vessel, and are instead returned to the sea. Discards may occur due to species being unmarketable or due to catch quota restrictions (Catchpole, et al. 2005).

Enforcement: Requiring compliance with the laws and regulations of the fishery.

Human observer: (i.e. at-sea observer) a person who monitors and records fishing activity while onboard a vessel for fisheries management measures.

Infrastructure: For the purpose of this report, infrastructure not only applies to the physical structures (i.e. vessels) and facilities but also the organizational structure (i.e. management framework) of the fishery necessary for operation.

IVQ/IFQ: Individual Vessel Quota or Individual Fishing Quota, i.e. catch shares.

Logbook: A record of fishing activity including catch, effort, location, discards, interactions with protected species, and other data. Logbooks are maintained onboard the vessel.

MCS: Monitoring, control, and surveillance to support measures of fishing activity and compliance of fisheries management regulations.

Monitoring: Collection of data from fishing activities that provides data on catch, effort and bycatch.

REM: Remote electronic monitoring for fisheries management, includes use of on-board cameras.

Remote monitoring: Use of a technology to monitor fishing activity. The review of the data the results from these technologies does not take place onboard a fishing vessel, i.e. not human observers.

Reporting: Reports submitted by vessels or fishermen, which detail catch and landings. Reporting can also include data on purchases made by dealers or processors (NMFS 2017).

Scaling: An increase in the adoption of an innovation from a small number (e.g. pilot study) to the whole (i.e. entire fishery within a national jurisdiction).

VMS: VMS is a satellite-based fisheries surveillance program that can provide consistent information on a vessel’s position and activity. Used within national jurisdictions (i.e. within exclusive economic zones).
Executive Summary
Management of the world's fisheries has become an increasingly important issue over the last several decades as numerous stocks have begun to decline, some more rapidly than others. Electronic Technologies encompass a suite of new technologies that can be used to monitor catch, gear usage, reporting, bycatch, and vessel activity. Within this paper, I summarize findings from a three-part study on the evaluation of electronic technologies in fisheries monitoring, control, and surveillance (MCS) world-wide. In Part I, I focus on the various electronic methods that are currently employed within managed fisheries and the distribution of programs that use these methods across the globe, focusing particularly on Remote Electronic Monitoring (REM) and Vessel Monitoring Systems (VMS). Only 16 REM programs, distributed among six countries exist in the world to date. In contrast, over 120 countries have implemented VMS programs. This includes both state-based programs, such as in Albania where the government requires every vessel in its country’s fleet to be equipped with VMS (Cobani, 2013), or regionally-based, such as the Parties to the Nauru Agreement (PNA) which require tuna purse seine vessels in the Pacific Islands to carry VMS (PNA, n.d.)

Part II is an extensive literature review on the utilization of REM within fisheries management. Specifically, I analyze successes and failures of the use of REM in fishery MCS programs. Further, I make recommendations on the application of the technology to fisheries management worldwide in support of the Environmental Defense Fund (EDF) Fishery Solution Center’s Global Electronic Monitoring Project. I identify seven elements of success via the 14 case studies examined for the purpose of this project. These elements resulted as consistent factors necessary to achieve successful implementation of electronic monitoring within a fishery management program.

In Part III, I take a deeper look into VMS by analyzing VMS data from mid-water trawling vessels in Sierra Leone. I use a Hidden Markov Model (HMM) to spatially distinguish between fishing activity and non-fishing activity to 1) determine the distribution of mid-water trawling effort of 16 vessels in Sierra Leone waters and 2) determine if industrial vessels may be fishing illegally in the Inshore Exclusive Zone (IEZ), which is limited to artisanal fishing only. The HMM determined three unique states of industrial mid-water trawling vessel behavior: (1) fishing behavior, characterized by medium-length step lengths and tighter turning angles (2) steaming behavior, characterized by a range of step lengths from short to long and very broad turning angles (3) idling behavior, characterized by very short step lengths and a range of turning angles. Out of 44,666 data points, the HMM classified 72% as fishing behavior. Eight vessels exhibited trawling behavior within the IEZ.
Introduction
Management of the world’s fisheries has become an increasingly important issue over the last several decades, as several stocks have begun to decline, some more rapidly than others. Over 50% of wild fish stocks worldwide have reached their scientifically sustainable catch limit or are overfished (FAO, 2016). The United Nations Food and Agriculture Organization (FAO) State of the World’s Fisheries and Aquaculture (SOFIA) Report in 2016 stated that world capture fisheries have stabilized, however several critics including Pauly and Zeller argue that without proper catch reconstructions, this might not necessarily be true (Pauly & Zeller, 2017). Further, these authors argue that the SOFIA Reports need to place more emphasis on which stocks are under-fished, fully-fished, and overfished. The percentage of stocks that are considered “under-fished” continues to decline, while the percentage of stocks that are either fully-fished or overfished exhibit an increasing trend; and these trends are expected to continue if current management schemes persist (Pauly & Zeller, 2017). The need to manage these fish stocks sustainably is imperative. Marine fish species that traverse multi-jurisdictional waters, known as straddling stocks, pose particularly complex issues for the development of policy, management, and enforcement strategies across jurisdictional boundaries. Illegal, unreported, and unregulated (IUU) fishing is a significant issue for both jurisdictional and international fisheries management. According to Agnew et al. (2009), IUU fishing contributes to losses between $10 billion and $23.5 billion each year worldwide (Agnew et al., 2009).

Within this paper, I summarize findings from a three-part study on the evaluation of electronic technologies in fisheries monitoring, control, and surveillance (MCS) world-wide. In Part I, I focus on the various electronic methods that are currently employed within managed fisheries and the distribution of programs that use these methods across the globe, focusing particularly on Remote Electronic Monitoring (REM) and Vessel Monitoring Systems (VMS). Part II is an extensive literature review on the utilization of REM within fisheries management. Specifically, I analyze successes and failures of the use of REM in fishery MCS programs. Further, I make recommendations on the application of the technology to fisheries management worldwide in support of the Environmental Defense Fund (EDF) Fishery Solution Center's Global Electronic Monitoring Project. In Part III, I take a deeper look into VMS by analyzing VMS data from mid-water trawling vessels in Sierra Leone. I use a Hidden Markov Model (HMM) to spatially distinguish between fishing activity and non-fishing activity to 1) determine the distribution of mid-water trawling effort in Sierra Leone waters and 2) determine if industrial vessels may be fishing illegally in the Inshore Exclusive Zone (IEZ), which is limited to artisanal fishing only.
Part I: Distribution of Program Types Worldwide

Electronic Technologies encompass a suite of new technologies used to monitor catch, gear usage, reporting, bycatch, and vessel activity in fisheries (NMFS, 2017). Currently, most fishery MCS programs operate using a combination of logbooks, dockside monitoring, observers, and sea and port inspections (FAO, 2002). However, logbooks have proven to be inaccurate and observers may be expensive and sometimes unreliable (Gerritsen & Lordan, 2011). Electronic Technologies include technologies such as onboard cameras, electronic logbooks (i.e. tablets), and satellite vessel monitoring (e.g. Automatic Identification Systems (AIS) and Vessel Monitoring Systems (VMS)) to provide more holistic, accurate, and efficient data collection. These technologies are also accompanied by analytical software and algorithms to filter through the massive amounts of data that result from the use of electronic technologies (NMFS, 2017). In Part I, I compare and contrast the use of these various technologies on a global-scale.

I. Types of Technologies

Remote Electronic monitoring (REM). REM includes technologies such as on-board cameras used to monitor and capture information on fishing activity including fishing location, catch, the time fishing occurs, discards, gear usage, bycatch, and interactions with protected species such as sea turtles, sharks and marine mammals (NMFS, 2017). Hydraulic and drum-rotation sensors signal when the vessel is within a certain speed and rotation and when the winch activates, both of which are indicative of fishing activity. These two sensors work to kick on the cameras, which are set to record these fishing activities. Figure 1 depicts a schematic of a standard REM system.

**Figure 1:** The schematic above depicts a standard EM system. Archipelago Marine Research Ltd. is one of the many companies who have designed these systems (Archipelago Marine Research, 2012)

Vessel Monitoring Systems (VMS). VMS has been utilized since the early 2000s and is required on fishing vessels by some fishing organizations or states in order to obtain permits (Gerritsen & Lordan, 2010). Most VMS systems are commercially available radio technologies that transmit vessel location to a private provider and local government authorities (Detsis et al., 2012). VMS is typically closed-access and data is only shared between vessels, private
providers, and government authorities due to privacy concerns. Figure 2 depicts a standard schematic of a VMS.

![Vessel Monitoring System](image)

**Figure 2:** The figure above depicts a standard system of a VMS satellite system, which uses a VMS satellite, GPS satellite, and land earth station to operate (AFMA, n.d.)

**Automatic Identification Systems (AIS).** AIS was initially developed for the improvement of vessel awareness and maritime safety in areas beyond national jurisdiction (ABNJ). Recently repurposed, AIS is now used to track fishing vessel movement and activity in order to provide broader coverage of fishing activities in high seas areas (Merten et al. 2016). With AIS, vessels transmit location, speed, heading, and other identifying information through very high frequency (VHF) radio in a Self-Organizing Time Division Multiple Access (SOTDMA) to receiving ends (USGS Navigation Center, 2016). SOTDMA allows for heavy traffic of signals; in other words, each AIS station transmits its signal via two VHF radio signals at a unique, regular transmission schedule, therefore the “slots” where the signals are received can be shared by more than one AIS station (i.e. more than one vessel) (USGS Navigation Center, 2016). These schedules are automatically coordinated with one another, allowing close to 100% throughput of signals from every vessel (USGS Navigation Center, 2016). Two types of AIS systems have been developed to track vessels at sea: terrestrial-based AIS and satellite-based AIS. Vessels with terrestrial-based AIS systems transmit to shore-based radio receivers. Terrestrial-based AIS were first developed and endorsed by the International Maritime Organization (IMO) to improve navigational safety and prevent at-sea collisions (Cervera et al., 2010). Two classes of AIS systems also exist: Class A and Class B, where Class A has the capability to receive and transmit AIS signals and Class B can receive signals but cannot transmit them (USCG Navigation Center, 2016). Satellite-based AIS has emerged as an improvement to expand the limited coverage of terrestrial AIS systems. In the case of satellite AIS, information is transmitted via VHF to the constellation of low earth orbiting (LEO) satellites. While the prospects of using satellite-based AIS to better monitor global vessel activity are promising, there are significant flaws, including satellite capacity (Cervera & Gines, 2008), vessel compliance (McCaughey et al., 2016), and uneven government regulations. Figure 3 depicts how the SOTDMA system works within AIS.
**FIGURE 3:** The figure above displays an AIS system, and details how the SOTDMA receiving system works (USCG Navigation Center, 2016).

**Other Technologies.** “Other technologies” refer to those that do not fit within the 3 definitions described above. These include, but are not limited to, electronic logbooks, tablets, and cell phones. These technologies can be used to aid dynamic ocean management (DOM) efforts. For example, the West Coast groundfish fishery in Morro Bay, California uses iPads that were provided via TNC grant funding for fishermen that volunteered to participate in a program, eCatch. Fishermen are able to use eCatch – an automated reporting system that links GPS data with data about catch composition and quantity, entered by fishermen. The eCatch app for iPad allows for real-time modification of fishing closure areas within 1-2 days based on hot spots that pop up. Using this information, managers are able to reduce bycatch levels by rapidly responding to areas of high bycatch and closing these areas for limited amounts of time (Molteni, 2013).

**II. Comparison of Electronic Technologies and Programs on a Global Scale**

In the past, studies have been conducted which compare VMS to logbook data or observer records (Lee et al., 2010; Chang & Yuan, 2014). Outputs of these studies have included a raster file of catch per unit effort based on activity (Lee et al., 2010). Chang & Yuan (2014) found that nearly 20% of days classified as fishing via VMS technologies are not found in logbook-recorded fishing days, suggesting that logbooks are not a sufficient way to record fishing activities due to incomplete coverage, shifts in reporting dates, and non-reporting of fishing days (Chang & Yuan, 2014). VMS can be insufficient on its own, as some vessels fail to comply with their respective country’s requirements, and no uniform regulations exist across all nations (Detsis, et al., 2012). Whereas VMS is a technology that has existed and was implemented in MCS programs starting in the early 2000s, REM is a newer technology that has only recently been adopted by MCS programs. Only 16 REM programs, distributed among six countries exist in the world to date (Figure 4). The United States has created 8 different REM programs in fisheries such as the Atlantic HMS Longline fishery, in order to comply with its ICCAT
requirement (Atlantic HMS EM Program Summary, 2016), the Small Boat Longline Fleet in Alaska (Alaska’s Small Boat/Longline REM Program, 2016), and the Non-Pollock Trawl fishery in the Bering Sea/Aleutian Islands (Alaska Region EM Program Summary, 2016). Canada uses REM as a part of a very successful monitoring program within the British Columbia Groundfish fishery (Stanley et al., 2015), while New Zealand will require all commercial vessels to be fitted with and REM system in 2018 (IEMRS, 2017).

In contrast, over 120 countries have implemented VMS programs (Figure 5). This includes both state-based programs, such as in Albania where the government requires every vessel in its country’s fleet to be equipped with VMS (Cobani, 2013), or regionally-based, such as the Parties to the Nauru Agreement (PNA) which require tuna purse seine vessels in the Pacific Islands to carry VMS (PNA, n.d.). VMS is not limited to developed, data-rich countries such as the United States, Canada, and Australia as REM has been thus far. Although VMS systems are “required” on vessels in a large number and wide variety of nations, enforcement is varied across states and programs. Several countries collect VMS data; however, fewer actually analyze these data and use them for enforcement of regulations (e.g. time-area closures).

The International Maritime Organization (IMO) requires terrestrial AIS on tanker and passenger vessels over 150 metric tons, on international voyager vessels over 300 metric tons and on domestic voyage vessels over 500 tons (IMO, 2001); however nations and regions can require more strict regulations. For example, the European Union (EU) requires all fishing vessels of 15 meters or greater to be fitted with AIS, which equates to nearly 8000 vessels as of 2016 (Eurostat, 2017). However, a study by Natale et al. in 2015 found that only about 75% of vessels over 15 meters have actually adopted AIS (Natale et al., 2015). The United States requires commercial fishing vessels of 65 feet (19.81m) or greater to carry AIS. As of 2011, 24,964 vessels, 6,270 of which are fishing vessels, carry AIS in the U.S. (USGC, 2011).

Each technology has several advantages and disadvantages. Whereas VMS programs are more common and are required on a larger percentage of fishing vessels, signals are often required to be emitted only every 2 hours (McCauley et al., 2016). AIS signals are typically emitted more frequently and can be as regularly as once per minute. A received AIS or VMS signal often includes the position, speed, heading, and vessel identity of the ship, at a minimum (Merten et al., 2016). Because satellite signals are transmitted at a fine spatial-temporal resolution, these data can actually be used to supplement logbook information to create more detailed and accurate pictures of fishing activity. This type of comprehensive data can be used to visualize the spatial distribution of various fishing activities. AIS provides an extended view into global fishing effort by providing data in areas beyond national jurisdiction ABNJ, whereas VMS is limited to areas within individual country’s coastal area (Kroodsma et al., 2018; Natale et al.; 2016). Methods have also been developed to apply an unsupervised classification to AIS data in order to detect low-likelihood behaviors of fishing activity via algorithms, and to predict vessel trajectories (Pallota et al., 2013; Merten et al., 2016).
**FIGURE 4:** This map displays the distribution of countries currently employing and maintaining REM Program. The U.S., Canada, Australia, New Zealand, Denmark, and Scotland all contain an REM program in at least one fishery within its water.

**FIGURE 5:** Nations included in this designation include those where there is evidence for at least one vessel required or volunteering to carry VMS as a part of either a state-based or regionally-based program. This is not an exhaustive list and does not account for whether or not the countries are analyzing the data or using the data for enforcement measures.
Part II: Evaluation of the Implementation of Remote Electronic Monitoring

REM is an innovative tool for fisheries management that has not yet achieved wide-scale implementation. Although several successful pilot studies have been conducted all over the globe, examples of successful implementation at the country/national scale are few and far between. Stakeholders in marine fishing industries need tools to help evaluate opportunities for uptake of REM into their fisheries. The goal of this project is to explore the global experience of electronic monitoring in order to evaluate why uptake of REM has not been more common. This paper aims to identify best practices that would support wide-scale implementation of REM as an important tool within a fishery management system. With resources like this one, fisheries managers will have the information to support the use of REM for monitoring and enforcement, which may ultimately lead to better fisheries data to be used for behavioral accountability and improved long-term sustainability of fish stocks.

I. Methods
The methodology was completed in a three-step format. First, EDF’s electronic monitoring resources were organized into Podio1, an online database platform. The purpose of this database is to aggregate and tag EDF’s resources on Electronic Monitoring studies. The database currently consists of 41 documents, classified and tagged by eight different categories including geographic region, program goal, gear type, and species. Secondly, 14 case studies from across the globe including the U.S., Canada, the European Union, New Zealand and Australia were reviewed to identify common enabling conditions as well as barriers to REM program implementation. The results from these case studies were assessed for common elements of successful uptake, with particular connections made to the scaling principles detailed in Battista et al. (2017). Battista, et al. (2017) were able to identify several principles that are statistically correlated with various levels of successful scaling. Elements of success include 1) clear goal, 2) industry buy-in, 3) proper infrastructure, 4) cost-benefit analysis, 5) transparency, 6) flexibility, and 7) timeline. Therefore, for the purpose of this study, we define success as an electronic monitoring program that is durable and scaled to the entire fishery.

II. REM: Barriers to full-scale implementation
Costs. There are several barriers to implementation that are preventing uptake of REM within fisheries throughout the world. One of the most obvious barriers is deciding who pays for the costs of the technology. Fisheries differ on management arrangements and organization. For example, even within the United States, significant differences exist between fisheries management arrangements on the East Coast and fisheries management arrangements on the West Coast. Traditionally, the government (i.e. the National Marine Fisheries Service (NMFS)) on the East Coast, and particularly in New England, have paid for the majority of MCS costs. However, on the West Coast, fishermen have typically been responsible for these payments.

Theory of Adoption. Many authors have described different theories for explaining how a new innovation can spread throughout a society or a group of people. Seminal theories include the Diffusion of Innovations Theory (Rogers, 1962), the Threshold Models of Collective Behavior (Granovetter, 1978), the Trans-Theoretical Model of Change (Prochaska and DiClemente, 1982),

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1 https://podio.com/ by Citrix Systems, Inc.
and the extension of these theories applied specifically to the spread of new technologies presented in the influential book *Crossing the Chasm* (Moore, 2002). In essence, these theories suggest that different individuals have varying “thresholds” in the number of their peers who must first adopt a new innovation or technology before they themselves will begin to use it. Thus, a certain percentage of the population needs to adopt a new technology in order for it to take hold and become the norm (Battista et al., 2017). Furthermore, different groups with different values, preferences, and risk tolerances will look for different support features in a new technology, and will respond to different types of messaging about it (Rogers, 1962; Moore, 2002). Related more specifically to REM, self-monitoring (i.e. logbooks) or human observers are currently the norm for MCS programs. Fishermen and managers may be resistant to adopting a new technology, such as onboard cameras or satellite monitoring because they may be apprehensive to this type of change.

**Inadequate Infrastructure.** A major barrier to implementation is inadequate infrastructure. In this case, infrastructure not only refers to the structure of the individual vessels within the fleet, but also the framework of the managing body. There is no “one size fits all” approach to the use of REM. Different factors influence each fishery such as gear type, including single gear and multi-gear; species, including single species and multi-species; geographic region, including distance from port; and management strategy, including full retention fishery versus discard allowances, etc. It may be the case that existing REM programs have been designed to function within the specific features of the fisheries where they are being piloted, making it difficult for them to spread to other fisheries where conditions and requirements for success differ. In fact, another scaling principle is that the pilot sites (i.e. fisheries) should be selected where the conditions are representative of those that are likely to be encountered throughout the target geography (Battista et al., 2017).

**Privacy.** Along with these new technologies, privacy concerns have emerged as a barrier. Electronic monitoring allows for a large quantity of data to be collected on individual vessels and their fishing activity. Considerations must be made to safeguard the privacy rights and expectations of fishermen and their vessels (McElderry et al., 2007). Part of this expectation of privacy means that, in many cases, the data should not be used outside of the established fishery management objectives (Piasente et al., 2012).

**Scaling.** Finally, as previously mentioned, several pilot studies have been conducted worldwide, though few of these studies are translated into actual implementation. Scaling from a pilot study up to fishery uptake is perhaps the most prominent barrier to success. In several of these pilot studies, efforts to scale have not been an explicit part of the planning process. Recent research indicates that for scaling to be successful a deliberate and intentional scaling strategy must be developed and implemented from the earliest stages of innovation design (i.e. pre-piloting) throughout the life of the scaling effort (Battista et al., 2017).

### III. Remote Electronic Monitoring: Elements of successful full-scale implementation

To counteract these barriers, I identified seven elements of success via the 14 case studies examined for the purpose of this project. These elements resulted as consistent factors necessary
to achieve successful implementation of electronic monitoring within a fishery management program.

**Clear Goal:** Firstly, implementing REM technology is not a fishery management goal, but rather a tool that can address specific fishery management challenges. A clearly defined management goal and objective needs to be established first and foremost. Only thereafter can managers determine how REM can support this goal. Further, this singular objective is needed to drive the majority of the decision making throughout the program planning process.

**Industry Buy-In.** Secondly, a participatory environment must exist. Similar to most other environmental and conservation challenges, in order to invoke change, stakeholder buy-in is a crucial component, and this buy-in is likely to be lacking in systems where stakeholders are excluded from the design and implementation processes (Ostrom, 1990; Olsson et al., 2004; Reed, 2008; Campbell et al., 2010). The process of bringing the technology to scale needs to be participatory to ensure fairness for all fishermen.

**Well Developed Infrastructure.** Since lack of infrastructure can be a major barrier, proper infrastructure and planning for these framework challenges can be a solution. When both internal barriers (e.g. ensuring that the fishermen’s operations occur in front of a camera) and external barriers (e.g. building a constituency and generating industry buy-in) are identified, and then managed or removed, successful programs more frequently result (Battista et al., 2017). In some cases, it may be possible to design new REM technologies to take advantage of existing scaled infrastructure, rather than requiring the creation or spread of new infrastructure systems. For example, designing REM data collection portals to work on fishermen’s existing smart phones and cellular networks may make uptake easier and more likely than if fisheries must purchase new devices (i.e. tablets) to collect the data.

**Cost-Benefit Analysis.** A cost-benefit analysis and the act of comparing needs against budget throughout the design process can allow for more efficient and effective use of funds to determine tradeoffs among various management and monitoring systems. In addition, costs can be minimized if scaling is considered at the outset because manager can take advantage of economies of scale.

**Flexibility.** The program must be flexible, with processes for evaluation and adjustment as needed built into program design. This element allows for adaptation as technologies and methods improve, and also leads to the provision of tangible results of the program, which can help to bolster industry buy-in.

**Transparency.** Transparency must exist in all aspects of the program, including the data needs, data processing, and information sharing components. This component is especially important when dealing with adoption of a new technology and generating industry buy-in.

**Explicit Timeline.** Finally, a timeline that includes set deadlines and incorporates scaling principles at all stages of the project can help lead towards successful implementation. Several REM pilots conclude that the technology can be used to achieve monitoring needs, however when deadlines for progress are not present, these studies often fail to scale.
Figure 6 shows an implementation model of these seven elements, emphasizing the process of implementing EM into a fishery management plan. The following section takes a deeper dive into each element, with complimentary case studies to exemplify how the element resulted in success.

**Figure 6:** The figure above shows a schematic of the process for implementing REM into a fishery management plan. The management goal/need is the overarching driver for the entire process that guides the decision making. REM can then be used as a tool to support and achieve this management goal. The involvement of industry and an informed cost-benefit analysis is an iterative and adaptive process, which works as a feedback loop as decisions are made and the program is designed. Infrastructure needs and removal of barriers feed into the supporting technology after the program goal and technology have been established. The entire process and design needs to be flexible and transparent. Finally, the explicit timeline acts as a wedge that keeps the process structured with a target end date.

1) **Clearly Identified Goal with Supporting Objectives**
The objective of a fishery management plan guides the vision for change. Often, fisheries managers become captivated by a monitoring option and use that as the driver for the management planning process (Stanley et al., 2015). Managers may focus too much on implementing the REM system and lose sight of the larger sustainable fishing goals. REM alone is not the solution to overfishing nor should it be considered a goal in and of itself. REM be used to support a fisheries management objective(s) or address specific challenges, however limitations of the tool need to be recognized and taken into account. Therefore, rather than choosing the tool first, the goal of the fisheries management plan must be decided upon initially (e.g. achieving Maximum Sustainable Yield (MSY), avoiding bycatch, reducing effort, etc.). The management goal should then drive the decision-making throughout the rest of the planning
process, including the selection of the appropriate technology or combination of technologies that can be used for monitoring, control, and surveillance of progress towards this objective (Stanley et al., 2015). There are several potential foci of fisheries monitoring programs including, but not limited to: 1) Catch quantification (i.e., number of hooks); 2) Catch identification (both target species and non-target species); 3) Interactions with protected species (e.g. sharks, sea turtles, seabirds, and marine mammals); 4) Season and/or area compliance (i.e., seasonal closures; marine protected areas); 5) Discard monitoring; and 6) Fishing effort quantification (Sylvia et al., 2016). The management body must understand the limitations that accompany each type of monitoring program in terms of what can be monitored and what can be achieved.

a. Management Goal Success Story: Hawaii Longline Fishery
The goal of the Hawaii shallow set and deep set longline fishery managers was clearly defined when a pilot study was conducted in 2010 (McElderry et al., 2010). The goal of the program is to decrease interactions with protected species such as leatherback and loggerhead sea turtles and seabirds such as wandering albatross. The monitoring goal was therefore to assess non-target species interactions, specifically with seabirds and sea turtles (McElderry et al., 2010). A secondary objective was to count the number of hooks in each set. Based on the pilot study, researchers found that REM was successful in identifying all protected species via review of video footage (McElderry et al., 2010). Currently, 6 Hawaii longline vessels have been installed with video monitoring equipment with plans to phase-in more video equipment within the fleet each year. As of June 2017, the Western Pacific Regional Fishery Management Council (WPRFMC) put out a Request for Proposals (RFP) for vendors to review an additional 35 longline trips (WPRFMC, 2017). The goal encompassed a primary driver for action within this fishery, along with various other enabling conditions – therefore, progress is being made yearly towards the goal’s achievement.

b. Management Goal Success Story: British Columbia Rockfish Fishery
From 1990 onwards, many sectors of the groundfish fishery in British Columbia, Canada, implemented an Individual Vessel Quota (IVQ) management scheme (Stanley et al., 2015). The IVQ system was implemented in an effort to achieve maximum sustainable yield of yelloweye rockfish and to increase economic vitality of the fishery. REM was implemented as a tool to provide adequate catch monitoring of all catch retrieval operations. The secondary supporting objectives were to track all quota and non-quota species. Because the overarching goal was an IVQ for yelloweye rockfish, managers assumed this strategy would also suffice for protection of other quota species (Stanley et al., 2015). In 2006, a comprehensive electronic monitoring program was adopted for the six fishery sectors managed by IVQs, encompassing 16 species. Using this overall goal, British Columbia created a specific objective for each component of the program, as described in Table 1 (Stanley et al., 2011; Stanley et al., 2015).

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2 The yelloweye rockfish fishery is just one of the various target species in the overall fishery.
3 This table was adapted from Table 2 in: Stanley, R. D., McElderry, H., Mawani, T., & Koolman, J. (2011). The advantages of an audit over a census approach to the review of video imagery in fishery monitoring. ICES Journal of Marine Science: Journal du Conseil, fsr058.
TABLE 1: COMPONENTS OF THE B.C. GROUNDFISH HOOK-AND-LINE CATCH MONITORING PROGRAM

<table>
<thead>
<tr>
<th>Element</th>
<th>Objective</th>
<th>Coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hails</td>
<td>Confirm valid fishing trips</td>
<td>100</td>
</tr>
<tr>
<td>Logbooks</td>
<td>Create complete record of fishing operations</td>
<td>100</td>
</tr>
<tr>
<td>EM sensor</td>
<td>Collect complete sensor record of trip; Verify logbooks; Confirm valid fishing locations</td>
<td>100</td>
</tr>
<tr>
<td>EM imagery</td>
<td>Collect complete image record of catch retrieval operations; Random review to audit logbook catch record</td>
<td>100</td>
</tr>
<tr>
<td>Dockside monitoring</td>
<td>Verify record of species and weights of landed catch; Individual counts by species of landed catch</td>
<td>100</td>
</tr>
</tbody>
</table>

Hails refer to the hail-in and hail-out by harvesters as they provide notification of intent to leave for a fishing trip and return to unload from a fishing trip, retrospectively. EM refers to the REM component of the program.3

Adapted from Stanley, et al. 2011

2) Industry Buy-In and Support
Battista, et al. (2017) identifies “long term support to user” and “project design that turns users into partners” as two important principles for explaining successful scaling. This is consistent with case studies where REM pilot studies have moved to full-scale implementation. Fishermen participation and leadership in the design and implementation process allows for a decision infrastructure that incorporates dialogue, feedback, and compromise (Stanley et al., 2015). Fisheries that have set a precedent of a participatory process will likely find greater success due to mature leadership and established collaboration (Stanley et al., 2015). If managers, industry, and scientists can all be at the same table to discuss priorities and tradeoffs, there is a higher probability that fishermen will take ownership of the process (a key scaling principle, per Battista et al., 2017) and will continue to stay engaged since the outcomes will be applicable to their concerns (Johnson et al., 2004; Lynan et al., 2007). Encouraging partners to be open and comfortable from the beginning supports the idea that the challenge of having different bottom lines can be alleviated when a collaborative environment is built around shared interests, needs, and priorities (Robinson, 2017). Results of these partnerships while implementing REM include increases in the accuracy of fishermen’s logbook data, communication of the vision, the likelihood that vessel personnel will ensure proper performance of the monitoring system, and achievement of conservation goals of the fishery.

a. Industry Buy-in Success Story: Australia Eastern Tuna and Billfish Fishery
An audit-based REM video program was implemented in the Eastern Tuna and Billfish Fishery (ETBF) in 2015. A pilot study conducted prior to implementation concluded that the audit-based
REM program would achieve success and could be scaled to full-fishery implementation if industry buy-in exists from the initial phases of the process (Piasente et al., 2012). Further, results determined from the monitoring program need to be “transparent” so that managers can gain the trust of the fishermen and other stakeholders, therefore allowing the industry buy-in will to continue. As such, communication and collaboration with fishermen must be a priority going into the planning process (Piasente et al., 2012). As a result, this program compared the audits to the fishermen’s own logbook data – giving the fishermen responsibility and accountability which prompted improved logbook reporting and improved catch data overall; a theme that also occurred within the B.C. fisheries. Industry buy-in from the start eventually drove a behavioral change as fishermen were able to receive real-time feedback from logbook outputs, as well as consequences of poor reporting of protected species interactions (Piasente et al., 2012). Within the pilot study conducted in 2009, reporting improved and measures to mitigate interactions with protected species increased (Piasente et al., 2012). The program was fully implemented in July 2015. In 2016, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) reported that four out of the five species in the ETBF (i.e. striped marlin, swordfish, albacore, and yellowfin tuna) are not overfished, while one species (bigeye tuna) is overfished. This study concluded that the increase in net economic return observed in 2015 may be a result of the individual transferable quotas that the REM system supports (ABARES 2016).

b. Industry Buy-in Success Story: British Columbia Groundfish Fishery

The REM program within the British Columbia groundfish IVQ system has the confidence of the majority of the fishermen. Industry members were involved throughout the entire planning process and helped to determine which components should be a part of the overall program. As a result, the industry is able to understand the purpose of each component and how they impact the overall results relative to their needs and priorities (Johnson et al., 2004; Lynan et al., 2007). The program provides flexibility, allowing for fishermen to choose between the audit-based REM systems and carrying a human observer. A high percentage of the fishermen are receiving “passing scores” based on the comparison of REM imagery to logbooks. If a fisherman receives a failing score, he or she incurs the cost of a 100% review of the imagery from their fishing trip (Stanley et al., 2015). A retrospective study has found that the system has led to higher accountability and higher accuracy in data logbooks. Whereas before, fishermen lacked incentive to keep accurate logbooks, now fishermen are unlikely to bias their logbooks due to a combination of the REM imagery program and the dockside monitoring program (Stanley et al., 2015).

3) Planning for infrastructure needs and removing barriers to implementation

Battista, et al. (2017) suggests that managing external factors and utilizing existing scaled infrastructure can both lead to more success when attempting to scale up. “Infrastructure” as related to REM implementation refers to two different components: a) Equipment and Operations and b) the Management Framework. Since the theory of adoption is a significant barrier, improving infrastructure can make the adoption the technology easier. There may be features of either or both of these components that already exist throughout the fishery. Designing an REM program to take advantage of these system features can improve the likelihood and speed of uptake. Proper infrastructure also influences stakeholder buy-in and allows for the achievement of the specific goal. In addition, if internal and external barriers to
implementation can be mitigated or removed prior to attempts to scale, success is more likely (Battista et al., 2017).

Equipment and Operations includes factors such as the number of cameras on vessel, the strategic camera placement, and the resolution of the cameras. The most important component of this element for the success of an REM program is the harmonization of the fishermen’s operations and behaviors with the cameras. Several REM pilots have failed as a result of inexperience with fleets and management procedures, which should be used to determine the best REM set-up and approach (McElderry et al., 2003). For example, demersal longline vessels need camera coverage of the hauling station and the immediate water area where the longline emerges, whereas pelagic longline vessels need cameras to cover the “hauling station, the area where the catch is boarded, and… the area around the sea door where catch is maneuvered” (McElderry et al., 2008). Several studies found that results can be significantly improved when managers work with industry to improve catch and handling procedures so that the activity occurs within the view of the placed cameras. As such, implementation and testing needs to occur well before the season starts so that these barriers to success do not impact the regular operation of the fishermen (Stanley et al., 2015; McElderry et al., 2008; McElderry et al., 2007; McElderry et al., 2003).

The management framework infrastructure concerns the distribution of the responsibilities among the harvesters/fishermen, the management body, and the video imagery reviewers/technical support. As previously mentioned, fishermen play a critical role in maintaining the function of the REM equipment. Battista et al. (2017) found that in order to achieve successful scaling, users must be empowered with the necessary skills. Therefore, fishermen need to be educated on all their responsibilities and any consequences that may result from failure to carry out these responsibilities. Again, this training should occur well before the season opens to ensure the smoothest possible operation while at sea. In addition, it is often preferred for a third-party to complete the video review process, independent of the governing entity (Guy, 2017; Stanley et al., 2015). This allows the program to remain impartial. Regardless of who the reviewers are, they need to be well-trained in species identification and software use prior to beginning review (McElderry et al., 2010). Decision makers also need to decide on how the imagery will be reviewed. Options include using an audit-based approach where a random selection of imagery is reviewed, a census-based approach where a selection of individual vessels imagery are reviewed, and whether or not image detection software will be used. Further, fisheries also benefitted from having staff resources nearby to assist with the technical aspects of the REM system to provide support by servicing and maintaining REM systems locally (which is another critical factor for scaling success (Battista et al., 2017).

a. Equipment and Operation Success Story: Hawaii Longline Fishery

The Hawaii Longline program incorporated the automated REM system where various sensors are used to distinguish vessel activities and trigger image operation during fishing operations only (McElderry et al., 2010). The benefits to this decision were two-fold 1) manual systems often fail to capture 100% of fishing operations due to fishermen forgetting to turn the system on and 2) fishermen felt more comfortable that the cameras did not record imagery 100% of the time and only during fishing activity (McElderry et al., 2010). In addition, as a result of the pilot, camera placement was improved so that multiple cameras provided synchronous imagery.
recording and were placed at angles that were harmonious with operations of longline retrievals. Multiple synchronous camera views improved resolution and provided enough coverage for reviewers to interpret hauling events at a specific level of species identification. While human observer data in a study of this system recorded 30 species EM observers were able to comparatively record 25 species. The fishery also has plans to develop and adopt standardized catch handling procedures to facilitate improved observation and detection of catch event by video reviewers (McElderry et al., 2010).

b. Management Framework Success Story: British Columbia Groundfish Fishery

Within the B.C. groundfish fishery management program, roles of each party are clearly defined, including responsibility of incurring costs. The harvester is responsible for ensuring the function of the REM equipment throughout the entirety of each fishing trip during the season. If the REM system stops working for any reason, the crew must cease fishing operations, and the vessel must return to port to ensure that the system is repaired before returning to sea (Stanley et al., 2011). This provides incentive for the harvesters to keep the system working at full capacity. The harvester is also responsible for arranging data recovery at the conclusion of each trip. The audit-based approach was also incorporated into the program (Stanley et al., 2009; Stanley et al., 2015). This allowed for more impartiality because the audited imagery was used to validate the logbooks of the fishermen by a third-party reviewer (Stanley et al., 2015). The fisheries manager set up an auditing system where for each vessel, 10% of fishing events are randomly chosen for review, with the caveat that at least one fishing event per trip must be included in that selection (Stanley et al., 2015). The responsibilities of each party are listed and explained in Table 2. The responsibilities are explicit and well-defined. Further, each party is well educated on their individual tasks (Stanley et al., 2009; Stanley et al., 2015).

Table 2: Responsibilities of each party within the British Columbia Groundfish Fishery

<table>
<thead>
<tr>
<th>Party</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvester</td>
<td>Ensure accurate logbooks; ensure operation of REM system on vessel; make arrangements for data recovery post-trip; pay for 75% of REM program monitoring costs (with the exception of failure of audit, then pay for 100% of a full review)</td>
</tr>
<tr>
<td>Department of Fisheries and Oceans (DFO)</td>
<td>Determine threshold for audit review; determine scoring system for audit review; pay for 25% of REM program monitoring costs</td>
</tr>
<tr>
<td>Reviewers</td>
<td>Review and analyze REM imagery data; provide audit score to fishermen</td>
</tr>
</tbody>
</table>

The DFO is the acting management body for the British Columbia groundfish fishery. Although fishermen on the west coast Canadian fisheries are typically 100% responsible for incurring monitoring costs, as a result of the new program, costs are shared between harvesters and the DFO (Stanley et al., 2009; Stanley et al., 2015).

c. The Whole Infrastructure Package Success Story: New Zealand Longline Fishery

Prior to program implementation, the New Zealand longline fishery identified elements of a successful long-term program based on lessons learned from several previously completed pilot studies (McElderry et al., 2008; Guy, 2017). A vital part of the program was to increase fleet awareness and provide outreach efforts in order familiarize fishermen with the technology and their specific responsibilities. Further, the management body built a monitoring program

19
governance framework, which was explicitly made objective and transparent to ensure high compliance (Guy, 2017). New Zealand also developed its program capacity, which required establishing a field service infrastructure with a well-trained staff. The management body committed to contracting video imagery analysis to a third-party service, independent of industry and government (Guy, 2017). New Zealand also established data sharing agreements, aware that industry support would depend on the rules surrounding how and when information was collected and used. New Zealand’s Ministry for Primary Industries (MPI) ensures that the REM data will not be used for purposes outside of the management and monitoring objective – observing interactions with protected species, in particular with marine cetaceans and seabirds (Guy, 2017). Finally, New Zealand was able to take advantage of existing infrastructure. Rather than starting from scratch the introduction of Integrated Electronic Monitoring and Reporting System (IEMRS) is an amendment to existing fisheries regulations. Reporting and monitoring (by human observers) is already required. IEMRS, therefore, seeks to take advantage of the existing infrastructure by making monitoring and reporting electronic, which allows for more accurate, integrated, and timely data (MPI, 2016).

4) Cost-Benefit Analysis Throughout Design
A central part of the planning and design process of an REM system should be to compare costs, benefits, and operational components associated with REM (McElderry et al., 2003). A formalized cost-benefit analysis (CBA) compares needs against the budget (Stanley et al., 2015). If a CBA indicates a positive net benefit, implementation is much more likely. There are several monitoring options and opportunities within the common and expanded definitions of REM. A CBA can lead to more efficient use of the technology by helping to decide which components of REM are necessary in order to achieve the management goals. The CBA forces the management body to stick to implementation for data needs, rather than preconceived biases towards a particular technology (Stanley et al., 2015; Piasente et al., 2012). A formal CBA allows managers to balance incremental costs with the added complexity of fulfilling data needs (Stanley et al., 2015). This checks-and-balance type system will help fishermen recognize that the need for monitoring is to achieve the management and conservation goal, rather than just unnecessary data collection. CBAs can even show that monetary benefits outweigh costs in some cases, such as New Zealand’s IEMRS program (Guy, 2017):

“In addition to enabling significant improvements in fisheries management, IEMRS is expected to generate economic benefit for New Zealand. The Cost Benefit Analysis undertaken for MPI’s 2017 Budget bid to support IEMRS identifies monetized costs of $83.2 million over 15 years (2018-32), compared to monetized benefits of $158.6 million in the same period. Monetized benefits result from, for example, securing and increasing access for New Zealand’s wild-caught seafood to premium markets that require assurance of sustainable fish production and ‘boat to plate’ tracking.”

Office of the Minister for Primary Industries, 2017

a. CBA Success Story: Australia Eastern Tuna and Billfish Fishery
A study used a CBA approach to evaluate the existing human observer program in comparison to two variations of REM system approaches. Although it can be more difficult to quantify benefits,
similar to quantifying ecosystem services and the benefits of conservation, the Australian Fisheries Management Authority (AFMA) found it valuable to not only determine costs versus benefits of various REM systems, but also to compare these systems to the human-observer status quo. Costs of the REM systems incorporated the costs of initial implementation, as well as the long-term operational costs, while benefits incorporated the reduced costs of using an REM system when compared to a human-observer program (Piasante et al., 2012). Piasante et al. (2012) reported that the “quantifiable benefits of electronic monitoring…in the form of potential saved costs from reduced observer coverage” were $587,520 per year, with an 80% uptake of REM in the 40-boat fleet. This CBA also proved that although the initial costs of implementation are higher than initial costs of other monitoring options, the long-term costs of REM were significantly lower than the status quo, and further, the benefits significantly outweighed overall costs. The various scenarios compared to the status quo provided tangible, realistic results to fishermen so that they could better understand the need for implementation of the monitoring program, leading to higher levels of industry buy-in (Piasente et al., 2012).

b. CBA Success Story: British Columbia Groundfish Fishery

Within the British Columbia Groundfish Fishery, a CBA was used to compare the additional costs and further complexity of fulfilling data and capacity needs. Managers compared absolute needs to achieve the management and monitoring goal against the budget at each step of the process (Stanley et al., 2009). Several barriers are introduced when attempting to implement an REM program, and as such, DFO carefully considered the risks of each barrier, collaboratively brainstormed potential solutions to remove these barriers, estimated the costs of each potential solution, and then weighed the costs against the risks to find the most efficient solution within the budget (Stanley et al., 2009). This constant comparison led to the “audit-based” approach over the “census-based” approach to video review (Stanley et al., 2009). Benefits of the audit approach heavily outweighed the census approach for this 100% retention fishery. Rather than reviewing 100% of fishing trips, within each trip, video footage from 10% of the fishing events that occur are reviewed and compared to fisher logbooks (Stanley et al., 2009). If the logbooks match the results of the REM video review within a specified tolerance, the logbooks become the official record of catch counts. The audit approach is more economically efficient in terms of data review and costs fishermen are responsible for paying. Further, since the trips reviewed are chosen randomly, the mean catch rate within the reviewed sets can be extrapolated by the total number of sets to provide an unbiased catch estimation for the fishery (Stanley et al., 2009).

5) Program Evaluation, Flexibility and Room for Improvement

An important element of any environmental program, but especially for REM program implementation since it deals with a new technology, is flexibility and allowing for improvement (i.e. adaptive management). Regular evaluation can lead to program improvements, particularly as this new technology continues to expand and advance. In fact, this is another factor identified as significant for scaling success by Battista et al. (2017) – evaluating the progress of the scaling effort based on agreed upon indicators and adjusting as necessary. A program will not be perfect in its first iteration, so it is important for all parties to expect challenges that will require adaptation and innovation. An iterative process allows for risk management and requires leaders from all sectors (i.e., management, industry, and science) to stay involved and proactive (Stanley et al., 2015). Flexibility also allows fishery management goals to be refined as progress is made and priorities shift (Piasente et al., 2012). It is also important to monitor results and outcomes of
the program, as well as indicators of scaling advancement, on a regular basis in order to evaluate progress and make adjustments to management plans and scaling strategies as needed (Battista et al., 2017). Tangible results of the program can also help to continue gaining industry buy-in and support if there is evidence that the program is improving economic viability, health of fish stocks, and data completeness.

a. Program Evaluation and Flexibility Success Story: British Columbia Groundfish Fishery
A retrospective analysis of the REM Program within the British Columbia Groundfish Fishery indicated that the built-in evaluation and flexibility allowed for greater program success. At the end of the first year of the program, managers learned that output catch data provided a platform from improvements to the program (i.e. it could be used as an indicator of program efficacy). Within year two, the industry realized that there were no consequences for poor catch recording in logbooks, and therefore the fleet was not incentivized to improve accuracy of logbook data (Stanley et al., 2015). Therefore, by the end of year two, managers realized they needed to provide strong evidence that the scoring system was legitimate and realistic. Managers then began to sanction fishermen whose logbooks were inaccurate to show that the audit-based scoring system has “teeth” and real consequences, by implementing requests for full review for vessels that received low review scores. Further, fishermen were held responsible for payment of this full review. This resulted in a behavioral change and an improvement of logbook catch data (Stanley et al., 2015).

6) Transparency in All Aspects of the Program
In order to achieve program success, transparency is a key factor – particularly since REM deals with a new and not commonly implemented suite of technologies. Surveys have found that there is a need to educate fishermen about what REM actually is and encompasses. There are several fishermen who are not opposed to at-sea monitoring but do not support REM, viewing it as invasive in terms of privacy and data collection. Often times these opinions are based on incorrect assumptions about when and where camera imagery is recorded, and who has access to the data (McElderry et al., 2003). There is particular reluctance to the black box approach where video imagery is submitted to a reviewer and a pass/fail score is given without any crosscheck against logbooks or evidence provided as to why. This leads to skepticism and lack of trust. To increase stakeholder buy-in and trust, the entire process of video review needs to be transparent and understandable to fishermen. An improvement can be made in many cases when the video imagery is cross analyzed with logbooks to foster a sense of ownership and willingness on behalf of the fishermen (Stanley et al., 2015). According to Battista, et al. (2017) programs more successfully scale when they take advantage of existing infrastructure – in this case, the logbooks that fishermen are already required to keep. When the new technology (i.e., REM) is meshed with the existing patterns (i.e., logbooks), the innovation is more likely to be understood and accepted.

a. Program Transparency Success Story: British Columbia
As previously described, the B.C. groundfish fishery adopted the audit-based approach to video imagery review for monitoring assessments. A key component of the program, however, is that the review of imagery simply acts as a check for the fisher logbooks. The program continues to determine official catch estimates based on the fishermen’s own logbooks and offload records
within the dockside monitoring program (Stanley et al., 2011). If managers use only imagery to determine the official catch estimates, this would result in a time gap between actual catch and the estimation of catch that, requiring a much heavier reliance on the REM system. This would increase the need for data storage capacity and review times. Secondly, estimates would be calculated in a “black box” (i.e., by third party reviewers the fishermen do not personally know), and therefore, fishermen would be hesitant to trust the results. Further, the catch estimation process remains familiar and intuitive to fishermen because it is based on their own records. The industry, therefore, trusts the resulting data and take precaution to ensure that their logbook recordings are accurate. This results in high compliance with the program which has led to economic improvement and achievement of conservation goals (Stanley et al., 2015).

7) **Explicit Timeline that Includes Scaling at All Stages of the Project**

Although scaling has been referred to throughout this report, this element explicitly details the importance of the incorporation of and planning for scaling at all stages of a project. Scaling cannot be an afterthought if full implementation is the ultimate goal of the REM program. A scaling strategy must be defined at an early stage, with specific targets set to achieve certain levels of scale. Managers cannot assume that scaling will automatically occur at the conclusion of a successful pilot (Battista et al., 2017). This point has been proven time and again, as numerous pilot projects throughout the globe have concluded with successful results, yet full-scale implementation has only occurred in a handful of fisheries worldwide. More often than not, organizations and management bodies dedicate extensive time, effort, and capital into the design and implementation an effective pilot project to stimulate the success of the innovative technology, yet do not prepare at the ground level for scaling up to ensure success of the program in totality. In addition, Battista, et al. (2017) identified agreement on a target pace for scaling as another critical factor in scaling success. Several REM pilots conclude that the technology can be used to achieve monitoring needs, yet offer no timeline for how to progress. Lack of predetermined times for uptake has resulted in negative outcomes while REM technologies languished.

   a. **Scaling Success Story: British Columbia Groundfish Fishery**

The DFO within Canada recognized the need for an effective monitoring program to achieve the desired outcomes of the IVQ program (Stanley et al., 2015). Since rockfish populations, yelloweye rockfish in particular, were in dire need an effective conservation program and fishermen’s economic vitality continued to diminish – the need for the program was immediate. The DFO created the IVQ program to improve socioeconomics within the fishery, but also created a tangible deadline by requiring the industry to improve upon monitoring, or else the fishery would be shut down in 2005 until the problem was fixed. This combination carrot and stick approach created both a bottom-up and top-down energy that drove the program forward towards implementation (Stanley et al., 2015). Scaling principles were included from the start of the planning process including a vision for change, stakeholder participation and leadership, a cost-benefit analysis, and risk management.

**IV. Overview: Process of Elements**

Evidence is not lacking that these elements of success lead to successful, full-scale implementation. The British Columbia groundfish fishery can be used and referred to as a model of implementing REM within a fisheries management framework. The program, from start to
present, exemplifies each of the elements, and demonstrates the significance of each as a key factor of the entire process. Figure 7 exhibits the REM Implementation Model in action for the B.C. groundfish fishery.

The management goal/need for the fishery was to achieve better fish stock conservation and improved economic vitality, which was achieved via the IVQ system. Common REM in the form of remote on-board vessel video camera monitoring was decided upon as the tool to support and achieve this management goal. Members of industry were involved in the planning process, generating buy-in to the monitoring system. An informed cost-benefit analysis was applied each time a new challenge presented itself. The potential barrier of loss of data due to manual operation of cameras was removed by implementing and automatic video imagery system. Responsibilities were explicitly delegated to all parties involved and fishermen were trained in the necessary skills to effectively conduct fishing operations alongside the REM system. Transparency was achieved by deriving official catch estimates via fishermen’s logbooks. Adjustments were made to the program after years 1 and 2 to improve upon effectiveness of the program. The impending 2005 fishery closure provided a deadline by supplying an official target date for full REM uptake.

**FIGURE 7:** The figure above shows the schematic of the process for implementing REM into a fishery management plan in action within the B.C. groundfish fishery. Box 1) The management goal/need for the fishery was an IVQ to achieve better fish stock conservation and improved economic vitality. Box 2) Common REM in the form of remote on-board vessel video camera monitoring was decided upon as the tool to support and achieve this management goal. Box 3) Members of industry were incentivized to be involved in the planning process and buy-in to the monitoring system. Box 4) An informed cost-benefit analysis was used each time a new challenge presented itself. Box 4) The potential barrier of loss of data due to manual operation of cameras was removed by implementing and automatic video imagery system. Box 5) Responsibilities were explicitly delegated to all parties involved. Box 6) Transparency was achieved.
by deriving official catch estimated via fishermen logbooks. Box 7) Adjustments were made to the program after years 1 and 2 to improve upon effectiveness of the program. Box 8) This mandate created urgency by supplying an official target end date.

V. REM: Failure to Scale
While it is important to evaluate success and disseminate how successful implementation was able to occur, it is also important to evaluate why so many other pilot projects failed to scale. REM pilots fail to scale for several reasons – most prominently due to lack of a clear, overarching goal and a lack of incentive or urgency to move onward to full scale implementation. The case studies below describe pilot REM projects that did not scale past this initial phase.

a. Failure to Scale: Tropical Tuna Purse-Seine Fishery
The goals of this pilot study were to use REM for consistent and accurate monitoring of fishing effort operations including counts and species identification for both retained and discarded catch of the tropical tuna purse-seine fishery, as well as to monitor interactions with sharks and sea turtles (Ruiz et al., 2014). These goals proved to be too intensive in order to achieve success, both within the pilot and when scaling up to full implementation. Goals should be simplified as much as possible to enable design of the most efficient and effective REM system. Results were highly variable among set-types for tuna catches. The pilot study concluded that the researchers struggled to find proper alignment between camera views and fishing (Ruiz et al., 2014). Camera placement (i.e., equipment and operations infrastructure) depends heavily on harmonizing the camera placement with both the intended management goal and the fishing operations. Four on-board video cameras simply do not provide enough resolution or coverage of the vessel and fishing operations to accomplish effective monitoring for all four goals listed above. Another key component of this study was that it took place in three ocean basins: Pacific Ocean, Indian Ocean, and Atlantic Ocean, coverage a large geographic area (Ruiz, et al., 2014). Therefore, this project covered not only a variety of regions and stakeholders, but also management bodies. Since industry buy-in and cooperation among invested parties is such a crucial component for scaling success, extra careful attention must be paid to organize and collaborate among groups that span such a large region.

b. Failure to collect sufficient data: Danish Cod Fishery
The Danish Cod fishery created a goal to use REM to provide 100% coverage of catches and discards in order to incentive fishermen to optimize catch selectivity under the Catch Quota Management system. The study found that the camera resolution was insufficient for discards, however this was in large part due to that catch handling procedures did not align with video camera placement (Kindt-Larsen et al., 2012). These objectives of covering 100% of both catches and discards are difficult to accomplish with a closed circulated television (CCTV) set up that includes only three of four cameras (Kindt-Larsen et al., 2012). The equipment and operations infrastructure requirement is different for catch coverage than it is for discard coverage. Discard coverage requires high resolution camera views of discard chutes. Camera positioning and as the number of discard chutes increases, time spent on image analysis and the accuracy of image analysis also increases. This may not be enough to incentivize fishermen to change their behavior – particularly when the study also lacked ability to generate industry buy-in and cooperation. If managers have two overarching goals, as exemplified here, they may need to implement two separate monitoring systems to meet the disparate goals. A study by Ulrich et
al. in 2015 looked at the quality of the data collected via the cod fishery REM program, and found that the program is not currently as effective as it could be largely due to the functionality of the REM equipment. Specifically, the study noted that if cameras are dirty or blurry, it is difficult to accurately identify and allocate species (Ulrich et al., 2015).

VI. Discussion

The most important takeaway to consider when planning for REM implementation into a fisheries management plan is that the overarching management goals are the most important component. REM on its own is not a fisheries management goal but is rather a tool that can be used in a variety of ways to address specific fishery management challenges, like accountability. Each overarching goal (e.g., catch quantification, catch identification, interaction with protected species, etc.) encompasses different requirements for data needs and costs. For example, if the objective is to minimize protected species interactions, a CCTV camera system could be used to monitor interactions between fishing gear and these species, and/or to evaluate the condition of these protected species before they are released. This system requires strategic camera placement for successful monitoring but does not require a large number of synchronized cameras. This in turn means the system is collecting less data which requires less storage capacity and is less costly than other types of REM designed to meet other management goals. If, on the other hand, the goal is to apply sustainable catch limits to individual species in a multispecies fishery, catch composition data will be necessary. This objective requires high resolution levels of monitoring in order to distinguish specific species (i.e., various species of rockfish). If resolution is low, reviewers will only be able to make generalized identifications. This type of goal requires synchronization of multiple cameras which leads to larger amounts of data requiring more storage capacity and higher costs. Different discard regulations also change the way an REM system may be used. For example, a full retention fishery where discards are prohibited allows for the use of the audit-based approach and may not require the video review to be as specific as a fishery that allows some discards.

As demonstrated in the case studies above, a collaborative process that generates industry buy-in and trains fishermen with the necessary operation skills is essential for a successful REM program, particularly when fishermen are responsible for maintaining the REM system onboard the vessel. Transparency throughout the planning process and within the program itself will help to support and gather industry buy-in. Although infrastructure requirements can create barriers to success, removal of both equipment and operational barriers, as well as clearly defining roles with the management framework can lessen the impact of these internal and external barriers. Comparing needs to budget throughout the planning process via a Cost-Benefit Analysis will lead to the most efficient use of funds. EDF’s REM Cost Drivers Tool can be used to evaluate the costs a number of these technologies will impose, and to link management goals to specific program and cost requirements. Evaluating the program’s progress at various check-points can lead to problem-solving and program flexibility to increase success. Scaling cannot be an afterthought within the planning process and must be an explicit component from beginning to end. Finally, there are several technologies that fall into the category of electronic monitoring. These technologies including video cameras, electronic logbooks, and satellite-based monitoring systems are not mutually exclusive and can be used to complement each other in order to achieve the management goal. The REM Implementation Model (Figure 6) can be employed, regardless of which type of REM technology is being considered for implementation.
Further research needs to be completed on technologies that fall into the expanded definition of REM. Particularly for the benefit of developing, low-capacity fishing nations and regions outside of the U.S., Canada, New Zealand, and Australia, studies must be conducted on how electronic logbook systems and satellite technologies could be used to improve monitoring of global fisheries. As organizations like Global Fishing Watch continue to support satellite technologies, transparency in the fishing world will increase which can better inform and drive sustainable fisheries management (GFW, 2017).
Part III: Analysis of VMS Data using a Hidden Markov Model (HMM)

Sierra Leone (Figure 8) is a small, developing country on the west coast of Africa that has a coastline of roughly 560 km (CIA, 2018). A 125 km continental shelf exists in the northern coast, while the total area of the Exclusive Economic Zone (EEZ) is roughly 105,000 sq. km (Thorpe et al., 2009; Seto et al., 2017). The fishing industry is important to Sierra Leone as both a food source and a capital market, and is the third largest contributor to Sierra Leone’s current economic growth (Kargbo, 2017). However, IUU fishing reduces this potential capital gain each year. Kargbo (2017) estimates that Sierra Leone loses US$29 million each year as a result of IUU fishing (Kargbo, 2017). A study published in 2017 by Seto et al. calculated that FAO estimates of catch in Sierra Leone, which includes all fishing sectors, are about 60% lower than that of reconstructed catches, and further indicated that IUU fishing is responsible for nearly 30% of all catch coming out of Sierra Leone (Seto et al., 2017). Additionally, Seto et al. calculated that the majority of industrial fishing is carried out by foreign fleets, including China, Korea, and various countries that are a part of the European Union (Seto et al., 2017).

The coastal industrial trawl industry – whose target species mainly include small pelagics like sardinella and mackerel – developed in West Africa after World War II and continues to be a lucrative industry as these fish remain high value in European and Asian markets (Seto et al., 2017; Virdin 2017). To trawl in these waters each year, non-Sierra Leone flag state vessels are able to obtain permits via Sierra Leone holding companies. Unfortunately, the fishing grounds occupied by industrial trawlers overlap with those of the artisanal fishing fleets. The artisanal fishery, which also comprises a subsistence fishery, includes vessels that range from one-person canoes to Ghana boats – which can hold crews of a dozen or more people (Thorpe et al., 2009; Seto et al., 2017). After reconstructing catch from 1950 to 2015, Seto et al. found that the small-scale fishery in Sierra Leone, specifically, accounts for significantly more catch that the national data that is supplied to the FAO each year (Seto et al., 2017).

The interaction between the foreign industrial trawl fishery and the small-scale fishery in Sierra Leone poses several threats to the natives. Combined legal and illegal industrial fishing result in the removal of tens of thousands of tons of fish from Sierra Leone waters each year (Seto et al., 2017). As the sustainability of fish stocks in the Sierra Leone EEZ continue to decline, the opportunity for the small-scale fishery to seek economic gain from the local stocks are diminishing (EJF, 2011; Thorpe et al., 2009; Seto et al. 2017). Further, the vital source of protein provided by fish – which accounts for 80% of animal protein within the diets of the nation’s people – is shrinking in a country where poverty is already rampant (Sheriff, 2005; Thorpe et al., 2009; Seto et al., 2017). To make an already dire situation worse, the direct interaction between industrial-scale vessels and small-scale vessels poses a dangerous condition for the artisanal trawlers in terms of safety, as industrial trawlers repeatedly destroy nets and even capsize boats of the local fishermen (Carnemark, 2015; Virdin, 2017).

In 2009, the governments of Sierra Leone and Liberia created the West Africa Regional Fisheries Program (WARFP) in collaboration with the World Bank (The World Bank, 2009). A VMS program, introduced in 2011, now requires all industrial-scale trawling vessels licensed in Sierra Leone to be fit with a VMS system. In 2012, the Sierra Leone Ministry of Fisheries and Marine
Resources collaborated with WARFP to establish a 6-mile Inshore Exclusive Zone (IEZ) off the coast of the country. This regulation permits only local artisanal vessels, to fish within the 6-mile IEZ, while industrial trawlers and other large-scale vessel must fish in areas outside the IEZ (Virdin, 2017; Carnemark, 2015).

However, even with the VMS system in place, the challenge of monitoring and enforcement remains. Although VMS data for registered and permitted industrial vessels are available, the capacity to analyze these data does not exist within the Ministry of Fisheries and Marine Resources. Conflicts between industrial fleets and small-scale vessels still occur on a regular basis, as described by an article that was released by The Economist in December 2017 (Nets akimbo, 2017). The author describes an incident that breaks out between a local artisanal fisherman and a foreign industrial fisherman, where the local fishermen accuses the industrial vessel of destroying his nets as the industrial trawler plowed through the IEZ (Nets akimbo, 2017). Countless stories like this one exist on a daily basis (Nets akimbo, 2017). As a result, this study aims to analyze Sierra Leone VMS data and find examples of industrial large-scale fishing vessels that make be breaking the 6-mile IEZ fishing regulation.

**Figure 8:** The figure above displays the country of Sierra Leone and the IEZ area from the coastline to 6-nautical miles where it is illegal for industrial trawling vessels to carry out fishing operations.

**Materials and Methods**
Recently, several papers have been published on distinguishing fishing activity from non-fishing activity and calculating fishing effort using AIS and VMS satellite vessel data (Kroodsma, et al.
Methods for distinguishing fishing activity from non-fishing activity differ based on gear-type (de Souza et al., 2016). For trawling gear, using a Hidden Markov Model (HMM) is one of the most published methods to determine fishing behavior (de Souza et al., 2016; Peel & Good, 2011; Borchers & Reid, 2008). Trawling activity is characterized by the towing of nets behind a vessel at low, constant speeds typically between 2.5 and 8 knots (de Souza et al., 2016; Vespe et al., 2016; Lee et al. 2010). A HMM assumes: 1) a series of observations exist, 2) that each observation is the result of an unobserved state, and 3) that each observation is independent of one another (Ghahramani, 2001). The HMM used for this study is a bivariate time series model, in which the step length and the turning angle at each observation point are calculated (Michelot et al., 2017). Step length and turning angles are a result of the underlying, unobserved state (Michelot et al., 2017). Since this model assumes a consistent time series (in this case, an observation every hour) step-length can also correlate to speed – an indicator of fishing behavior for trawling vessels.

The Duke University Marine Geospatial Ecology lab obtained Vessel Monitoring System (VMS) data from the Sierra Leone Ministry of Fisheries and Marine Resources. The dataset spans from September 1st, 2015 through August 31st, 2016 and includes information on the vessel location, speed, heading, and other identifying information (VMS Public Device Number and message ID). The Ministry of Fisheries and Marine Resources also provided a separate dataset where vessel identification information was provided and included vessel name, PLN number, IMEI number, and Public Device Number (Serial Number). I obtained additional fishing vessel license information from the Ministry of Fisheries and Marine Resources webpage, including updated license lists for 26th September 2016, 1st July 2016, and 15th May 2015. I used these data to extract information on vessel size, Sierra Leone holding company information, flag state, and gear type. I then subset the data to include mid-water trawlers only, and removed two vessels from this study due to an insufficient number of data points within its VMS file. A total of 16 vessels remained for use in this study (Table 3).

First, I created an XY VMS to Lines tool for use in ArcGIS (Appendix 3). This tool converts latitude and longitude coordinates from a raw VMS text file to a vessel track lines feature class. This tool allows for the visual assessment of VMS signals emitted from individual vessels over time. It can aid the identification of vessels who may be fishing or traveling illegally, both spatially and temporally. For example, it allows an analyst to see if a vessel entered a closed zone (i.e. a spatial area where fishing is not allowed) or if a vessel was active during a seasonal closure. The output includes a line feature class with the track number, the track start date, the track end date, and the average speed (in knots) during the duration of that track. However, this tool is limited in its use to distinguish between fishing and non-fishing behaviors. As a result, I used a Hidden Markov Model to determine where fishing activity is occurring within the Sierra Leone EEZ.

Raw VMS data are not suitable for use in HMM due to repetitive data points, missing data points, and aggregation of multiple undistinguished tracks into one file. To prepare the data, a consistent time-series of latitude and longitude coordinates and speed needs to be prepared for each vessel. I created a tool in python to categorize the data points by individual vessels. The tool then categorizes the data points from each vessel into “tracks”, distinguished by date and
time (see Appendix IV). If point \( x+1 \) is emitted less than 8 hours after point \( x \), the two points are assigned the same track ID. If point \( x+1 \) is emitted greater than 8 hours after point \( x \), point \( x+1 \) is assigned a different track ID. I created a second tool in python to interpolate latitude, longitude and speed (knots) data within each “track”. This tool uses the closest existing data points from the raw VMS file to create a consistent time array of every hour, and interpolates missing data using a linear spline method (see Appendix V). This is necessary because a state-space model assumes that the data are continuous and consistent. The “track” value allows the data to be aggregated into discrete periods of time, while still nested within the greater dataset of all fishing vessels.

I used the moveHMM\(^4\) package for the R programming language\(^5\) to implement the HMM. An HMM assumes there are a series of observations and a series of non-observable states (Michelot et al., 2016). The prepData function of the model calculates the turning angles and step lengths for the series of data (Figure 9). The user defines the number of states and the value of the initial parameters. The model also calculates the estimated maximum likelihood of the data for the specified set of parameters (Michelot et al., 2016). Although the purpose of the experiment is to identify two behaviors of the vessels (fishing and non-fishing), I set the model to fit three underlying states of movement: 1) fishing activity 2) non-fishing activity where the vessel is still moving, known as steaming 3) non-fishing activity where the vessel is not moving, known as idling. I used the same definition of fishing activity here as employed in de Souza et al. 2016, i.e. from when the trawl net is dropped into the water through when the net is fully retrieved onboard the vessel following the fishing operation (de Souza et al., 2016).

![Figure 9](image.png)

**FIGURE 9:** The figure above is from Michelot et al., 2016 and describes how step lengths (left) and turning angles (right) are calculated within the moveHMM package.

I excluded points within 2 nautical miles of the shoreline surrounding ports from the study, as industrial sized trawlers often travel at lower-level speed that can mimic trawling within these areas, even if no nets are set (Lee et al., 2010). I chose initial step length and angle parameters by fitting the model through several iterations of randomly selected parameters, followed by choosing the model with the highest maximum estimated likelihood. After all vessels are fit to the HMM, fishing effort is calculated by first, using the “Point to Raster” tool\(^6\) in ArcGIS\(^7\) to determine the

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\(^4\) Package ‘moveHMM’ (https://cran.r-project.org/web/packages/moveHMM/moveHMM.pdf)

\(^5\) The R Project for Statistical Computing (https://www.r-project.org)


\(^7\) http://www.esri.com/arcgis/about-arcgis
extent and cell size of the data. Second, the “Raster to polygon” tool\(^8\) converts the raster file to a polygon vector shapefile. Finally, using the “Count points in polygon” tool\(^9\) in QGIS, I calculate fishing effort that is normalized by “track”, therefore more weight is given to cells with a greater number of unique track points, than a cell with an equally large number of points from a single track.

**Results**

The HMM determined three unique states of industrial mid-water trawling vessel behavior: (1) fishing behavior, characterized by medium-length step lengths and tighter turning angles (2) steaming behavior, characterized by a range of step lengths from short to long and very broad turning angles (3) idling behavior, characterized by very short step lengths and a range of turning angles. The mean step length for the fishing state was 6.241 with a 95% confidence interval [6.188, 6.293]. The mean step length for the steaming state was 6.885 with a 95% confidence interval [6.721, 7.049]. The mean step length for the idling state was 0.046 with a 95% confidence interval [0.044, 0.048]. The most obvious difference in step length is the idling state, with a mean step length close to 0, which is in line with the definition of idling. The mean turning angle for the steaming state was 0 radians, while the mean turning angle for the fishing state ranged from -0.015 to 0.020, indicating that turning angles are sharper during fishing activity. Figure 10 displays the comparison among all three states for both turning angles and step lengths, whereas Figure 11 shows the fit of the model to these parameters. Deviation from normality is greater within the step length parameter; however, both the turning angle parameter and the step length parameter show a relatively standard normal distribution.

Out of 44,666 data points, the HMM classified 72% as fishing behavior. This equates to over 32,000 hours of trawling in the year 2015-2016 by 16 vessels. Figure 10c compares the results of the three states to the speed in knots correlated with each observation point. Trawling behavior is concentrated around speeds of 4 knots, while idling behavior is completely concentrated around the speed of 0, and steaming behavior ranges more widely from 0 to 12 knots. While the fishing, steaming, and idling activities that resulted from the HMM align with literature-specified speeds in knots for respective behaviors, the direct comparison between the simple speed filter and the HMM explains why a simple speed filter is not sufficient to determine vessel behavior. Figure 12 exemplifies this comparison further, by displaying an interpolated vessel track filtered by speed in knots at each point (Figure 12b) in comparison to the results of the HMM (Figure 12c). Not all points observed at speeds of 2.5-8 knots are classified as fishing behavior by the HMM. This indicates that a simple speed filter overestimates the number of points classified as fishing behavior. The HMM instead determines the state of a point by considering the “unobserved” state that occurred since the previous observation point via step lengths and turning angles.

The observation points from all vessels are dispersed through the larger coastal area of the Sierra Leone EEZ. These points are also highly concentrated along the northern coast where the continental shelf is wider (Figure 13a). The concentration of points classified as fishing behavior follow a similar pattern, however the denser cells are located closer to shore (Figure 13b). Fishing effort quantified as unique vessels per cell shows a high but more even distribution of fishing effort across the northern coastal area, indicating that fishing effort by individual vessels

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\(^9\) [https://docs.qgis.org/2.8/en/docs/user_manual/processing_algs/qgis/vector_analysis_tools/countpointsinpolygon.html](https://docs.qgis.org/2.8/en/docs/user_manual/processing_algs/qgis/vector_analysis_tools/countpointsinpolygon.html)
is dispersed relatively evenly throughout this northern area and fewer vessels are using the Southern continental shelf for fishing activity (Figure 14a). Fishing effort quantified as unique tracks per cell displays a more even dispersal of cells classified as high effort throughout the entire coastal area, indicating that while fewer vessels are using the Southern continental shelf, these vessels are making more trips to this area (Figure 14b). As many as 10 trawling vessels occupied the same 1.5 sq. mi. cell for fishing activity during the year of September 2015 to August 2015, while as many as 23 tracks occupied areas of high fishing effort throughout the year. The highest fishing effort area does not contain the largest number of unique tracks, which implies that vessels exerting more fishing effort are fishing longer per track. These results counter the assumption that high fishing effort would have equaled a high number of unique trawling vessels. A select few vessels exerted most of the overall fishing effort in very specific areas.

In the northern coastal area, fishing effort within the IEZ is concentration around the Port of Freetown – the largest seaport in the country (SeaRates, 2018). Illegal fishing within the IEZ is concentrated within the northern portion of the IEZ, close to the Ports of Freetown and Pepel, as well as in the southern portion of the IEZ along the narrower continental shelf (Figure 14). Table 3 provides information on each vessel including whether or not the vessel fished illegal within the IEZ at any point from September 2015 to August 2016. Figure 15 displays the location of the points classified as fishing behavior within this restricted zone by unique vessel. A greater number of vessels exhibited illegal fishing behavior near the Ports of Freetown and Pepel, in the northern region of the IEZ, and near the Port of Sherbo Island in the central region of the IEZ. Vessel #2 had the largest number of points classified as fishing behavior within the IEZ; however, concentrated primarily in the southern region of the IEZ.

<table>
<thead>
<tr>
<th>Public Device #</th>
<th>Company/Agency</th>
<th>Flag State</th>
<th>Illegal Fishing in IEZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tima F. Co</td>
<td>China</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Tima F. Co</td>
<td>China</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Tima F. Co</td>
<td>China</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Sierra Fishing Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Sierra Fishing Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Tima F. Co</td>
<td>China</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Sierra Fishing Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>Sierra Fishing Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Sierra Fishing Co.</td>
<td>China</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>Tima F. Co</td>
<td>China</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>Africa Yuhai F. Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td>Africa Yuhai F. Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Company Name</td>
<td>Country</td>
<td>Location</td>
</tr>
<tr>
<td>---</td>
<td>---------------------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>13</td>
<td>Kombra F. Co</td>
<td>St. Kitts and Nevis</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>Africa Yuhai F. Co.</td>
<td>China</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>Peninsular F. Co</td>
<td>Korea</td>
<td>Yes</td>
</tr>
<tr>
<td>16</td>
<td>Africa Yuhai F. Co.</td>
<td>China</td>
<td>No</td>
</tr>
</tbody>
</table>

**FIGURE 10:** Density distributions across the two model parameters: step lengths (a) and turning angles (b).

**FIGURE 11:** Quantile-quantile plot (qq-plot) for (a) the step length model parameter and (b) the turning angle model parameter.
FIGURE 12: Example of a track from vessel #8 showing (a) location of observation points (b) speed recorded from observation points, as resulted from XY VMS to Lines Tool (c) behavioral states resulting from HMM.
FIGURE 13: Mid-water trawling vessel points per 1.5 sq. mi. cell for 16 vessels over the period of September 2015 through August 2016. (a) All points, regardless of state, included to show point density over area. (b) Fishing effort determined by the summation of fishing behavior points per 1.5 sq. mi. raster cell calculated over the time period from September 2015 through August 2016.
FIGURE 14: Mid-water trawling effort of 16 vessels over the period of September 2015 through August 2016. This figure does not include data points that were classified as non-fishing behavior (i.e. steaming or trawling) by the HMM. (a) Fishing effort normalized by vessel. Higher weight (i.e. darker red cells) calculated for 1.5 sq. mi. cells in which several unique vessels exhibited fishing behavior within that cell. (b) Fishing effort normalized by track. Higher weight (i.e. darker red cells) calculated for 1.5 sq. mi. cells in which several unique tracks exhibited fishing behavior within that cell.
FIGURE 15: Vessels who demonstrated fishing behavior within the IEZ reserved for artisanal fishing only in the (a) northern, (b) central, and (c) southern portion of the Sierra Leone EEZ.

Discussion
Although fisheries management in Sierra Leone has developed as a result of WARFP over the last several years, monitoring and enforcement still need to improve in order to reduce conflict between the foreign industrial trawling fleet and the local small-scale fishery. Foreign fleets from China, Korea, and St. Kitts and Nevis continue to trawl in the IEZ area. Small-scale fishermen are, therefore, still at risk of injury or destruction of property. This conflict threatens not only the livelihood of these fishermen, but also the food and protein source that is brought in from sea for the subsistence of these fishermen and their families, in addition to the people of Sierra Leone who don’t have direct access to catch their own fish. Industrial fishermen likely will not abide by the IEZ regulation unless they have reason to believe that they will suffer consequences as a result of breaking the law.
As determined by the results, the flag state of the few vessels exerting high levels of fishing effort in exclusive areas is China. Further investigation should examine other common characteristics that may exist among these vessels such as vessel size, crew size, and how long these vessels have held their fishing licenses in Sierra Leone. From the social lens, more research should explore the industrial fleet dynamics. For example, since only a few vessels use such specific areas, there could be territoriality or a competitive exclusion that exists within this industrial fishery. These inter-fleet dynamics could prove useful in guiding further fishing regulations and limiting interactions between the industrial and artisanal fleets.

Although gaps in the data exist, the VMS program in Sierra Leone does gather sufficient data to be used within a HMM, following pre-processing steps. However, if the managers in Sierra Leone do not have a way to process these data themselves, the use of VMS for monitoring and enforcement remains limited. While the ArcGIS tool XY VMS to Line can give an indication of where and when industrial trawl fishing activity occurs, it is not sufficient to distinguish fishing behavior from steaming behavior for trawling vessels because it does not consider the underlying, unobserved state that occurs between points. The methods detailed in this study can be used for nearly any set of VMS industrial mid-water trawling data. As such, these types of methods should be transferred into user-friendly tools that can be applied by fisheries managers in developing countries such as Sierra Leone. Next steps for this study include packaging the methods explained above into two tools, one that can run in ArcGIS by a user with basic knowledge of Arc software and one that can be used with R software. The first tool is a VMS pre-processing tool. The purpose of this tool is to clean raw VMS data and transform it into a dataset that can be used with the HMM model. The second tool is a HMM-VMS tool, which applies the Hidden Markov Model to the pre-processed VMS data, and outputs points distinguished by the three behavioral states: 1) fishing behavior 2) steaming behavior 3) idling behavior.

Tool creation is an important part of capacity building and technology transfer to the fisheries managers within these countries, who need to be able to process the VMS data themselves. Sierra Leone does not have the means nor the capacity to monitor the entire IEZ area by patrol vessel on a regular basis. Perhaps, by using the two potential tools described above, managers can identify vessels that are regularly fishing illegally within the IEZ and use this evidence to focus their efforts in specific areas at specific times, making enforcement a more efficient process. Instead of putting effort towards gaining more resources, such as fuel and patrol boats, the managers and enforcement officers could instead shift their efforts and resources towards vessels, such as vessel #2, which are identified as repeatedly fishing illegally within the IEZ.

Despite the ability of the HMM to distinguish fishing behavior from steaming behavior and idling behavior, this model would benefit from the incorporation of ground truth data. Ground truth data, in the form of logbook data, at-sea human observations, or electronic monitoring footage, would provide a more accurate way to determine the initial step lengths and turning angle parameters used in the model. Further, ground truth points would allow us to determine false positives and false negatives of fishing behavior, as identified by the HMM, in order to better calculate model performance. In addition, the HMM presented here operates more reliably on vessel tracks that were more complete and required less interpolation.
Conclusion
Electronic technologies include on-board cameras, satellite vessel monitoring, and other technological advances that provide a new opportunity in fisheries management today. Use of these technologies can provide a more holistic understanding of the use and exploitation of fish stocks from a local to a global scale. Creating, refining, and testing tools which can be used to process data from electronic technologies is imperative to efficiently and effectively analyze these data. This type of research can 1) support wider uptake of these technologies 2) provide better information – both spatially and temporally – about fishing effort and compliance with fishing regulations, and 3) be used for accountability and long-term stability and sustainability of fish stocks. Further, the comparison of the scale and coverage of the various electronic technologies is becoming increasingly important to improve the efficacy of monitoring and enforcement of maritime activities in both coastal areas and the high seas.

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## Appendix

### I. Remote Electronic Monitoring Programs and Sources

<table>
<thead>
<tr>
<th>Country</th>
<th>Fishery</th>
<th>Percent Coverage</th>
<th>Number of Vessels</th>
<th>Spatial Extent</th>
<th>Notes</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Trawl Individual Quota (ITQ), includes midwater trawl, bottom trawl and fixed gear</td>
<td>40</td>
<td>US West Coast</td>
<td>EM is optional, either 100% human observer or EM</td>
<td>[<a href="http://ww">http://ww</a> w.pcouncil.org/wp-content/uploads/2017/04/Sup_IR3_WCR_ET_ImplementationUpdate_Apr2017-7BB.pdf](<a href="http://ww">http://ww</a> w.pcouncil.org/wp-content/uploads/2017/04/Sup_IR3_WCR_ET_ImplementationUpdate_Apr2017-7BB.pdf)</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>British Columbia Hook and Line Ground fish Fishery</td>
<td>100%</td>
<td>200</td>
<td>B.C. waters</td>
<td>Incepted in 2006. &quot;Today, 100 percent of British Columbia’s commercial hook and line and trap groundfish fishing is monitored using Archipelago EM technology, involving approximately 200 vessels, 1,200 trips, 10,000 sea days, and 20,000 fishing events annually.&quot;</td>
<td><a href="http://assets.wwf.org.uk/downloads/fisheriesmanagement_2_.pdf?ga=1.108155522.1679163135.1490304815">http://assets.wwf.org.uk/downloads/fisheriesmanagement_2_.pdf?ga=1.108155522.1679163135.1490304815</a></td>
</tr>
<tr>
<td>USA</td>
<td>Alaska Rockfish fishery</td>
<td></td>
<td>Gulf of Alaska</td>
<td>Catch processors can choose to use an REM monitoring system, in addition to other monitoring options</td>
<td>[<a href="https://alaska">https://alaska</a> fisheries.noaa.gov/fisheries/electronic-monitoring](<a href="https://alaska">https://alaska</a> fisheries.noaa.gov/fisheries/electronic-monitoring)</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>Cod fishery</td>
<td>23</td>
<td>North Sea and Skagerrak</td>
<td>Goals of the program: Evaluate the effectiveness of a “land-all policy”; Evaluate installation and operation of REM system.; Analyze training programs for REM analysts; Develop system to combine length measurements and fish counts; Use of REM in management advice</td>
<td>[<a href="http://emi">http://emi</a> nformation.com/1252/2010-and-ongoing-denmark-north-sea-skagerrak-program](<a href="http://emi">http://emi</a> nformation.com/1252/2010-and-ongoing-denmark-north-sea-skagerrak-program)</td>
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<tr>
<td>Country</td>
<td>Fishery Type</td>
<td>Fish Species</td>
<td>Area</td>
<td>Purpose</td>
<td>Additional Information</td>
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<tr>
<td>---------</td>
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<td>--------------</td>
<td>------</td>
<td>---------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Region</td>
<td>Fishing Method</td>
<td>Fishing Area</td>
<td>Recording Equipment</td>
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<tr>
<td>---------</td>
<td>--------</td>
<td>----------------</td>
<td>--------------</td>
<td>----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Small boat longline, halibut and sablefish</td>
<td>~8%</td>
<td>Southeast, Southcentral and Southwestern waters of Alaska</td>
<td><a href="http://emiinformation.com/859/em-in-the-npalaska-region">http://emiinformation.com/859/em-in-the-npalaska-region</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Hawaii longline fishery</td>
<td>4%</td>
<td>Hawaii/North Pacific</td>
<td>PIFSC installed 6 Hawaii longline vessels with REM system in 2017; goal in 2018 to continue installation in more vessels</td>
<td>httpp://www.wpcouncil.org/2017/06/16/hawaii-longline-electronic-monitoring-video-review/</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>Canadian groundfish hook-and-line fishery and groundfish trap fishery</td>
<td>100%</td>
<td>Bering Sea/Aleutian Islands</td>
<td>commercial groundfish hook and line and trap fishery = 100% at sea recording by REM system</td>
<td><a href="http://www.pac.dfo-mpo.gc.ca/fm-gp/docs/framework-monitoring-cadre_surveillance/page-3-eng.html#ftn1">http://www.pac.dfo-mpo.gc.ca/fm-gp/docs/framework-monitoring-cadre_surveillance/page-3-eng.html#ftn1</a></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>Eastern Tuna and Billfish Fishery, the Western Tuna and Billfish Fishery, and the Gillnet, Hook and Trap fishery</td>
<td>100%</td>
<td>Australia EEZ</td>
<td>REM systems required for most commercial fishing boats in the ETBF, WTBF, and the Gillnet, Hook and Trap fishery</td>
<td><a href="http://www.afma.gov.au/monitoring-enforcement/monitoring-electronic-monitoring-program/">http://www.afma.gov.au/monitoring-enforcement/monitoring-electronic-monitoring-program/</a></td>
<td></td>
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## II. VMS Programs and Sources by Country

<table>
<thead>
<tr>
<th>Country</th>
<th>Part of Agreement?</th>
<th>Number of Vessels</th>
<th>Notes</th>
<th>Source 1</th>
</tr>
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<tr>
<td>Country</td>
<td>Program Details</td>
<td>Vessels</td>
<td>Source</td>
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<tr>
<td>Argentina</td>
<td>CCAMLR, CONVEMAR</td>
<td>400 Inmarsat C</td>
<td>FAO Fisheries Report #696; OECD Review of Fisheries 2013</td>
<td></td>
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<tr>
<td>Australia</td>
<td>Vessels licensed to fish roughly in the area of the South East Fishery; Vessels licensed in Western Deepwater trawl fisheries; All catcher, carrier and processor boats in the Northern Prawn Fishery; Licensed Bass Strait Central Zone Scallop Fishery boats; Eastern Tuna and Billfish Fishery boats licensed to use pelagic longlines; Western Tuna and Billfish Fishery boats licensed to use pelagic longlines South-East Non-trawl boats that have activated the VMS trigger or wish to fish for quota species outside the AFZ Vessels licensed in the East Coast Deepwater Trawl Fishery Vessels licensed in the Coral Sea Fishery (other than aquarium boats)</td>
<td>500</td>
<td><a href="http://www.fao.org/fishery/vmsprogramme/VMS_AUAFMA/en">http://www.fao.org/fishery/vmsprogramme/VMS_AUAFMA/en</a>; <a href="http://www.afma.gov.au/fisheries-services/vessel-monitoring/">http://www.afma.gov.au/fisheries-services/vessel-monitoring/</a></td>
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</table>
All foreign licensed vessels must carry and operate an ALC (shipboard VMS unit) of a type approved by AFMA; Northern Zone Rock Lobster; Miscellaneous fishery (Giant crab); At-sea aquaculture operation

<table>
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<tr>
<th>Country</th>
<th>EU Regulation, South Pacific, CCAMLR</th>
<th>OECD Review Book - google link</th>
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<tbody>
<tr>
<td>Bahamas</td>
<td><a href="https://www.bahamas.gov.bs/wps/wcm/">https://www.bahamas.gov.bs/wps/wcm/</a></td>
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<td>Aquaculture+Sector+Review+17Nov16.pdf</td>
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<td>?MOD=AJPERES</td>
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<tr>
<td>Bangladesh</td>
<td>trawlers and ships</td>
<td><a href="http://www.dhakatribune.com/">http://www.dhakatribune.com/</a></td>
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<td></td>
<td>bangladesh/2016/06/28/govt-install-</td>
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<tr>
<td></td>
<td>vms-fishing-vessels/</td>
<td></td>
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<tr>
<td>Belgium</td>
<td>CCM, WCPFC</td>
<td><a href="https://www.wcpfc.int/system/">https://www.wcpfc.int/system/</a></td>
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<tr>
<td></td>
<td>files/WCPFC%20-TCC6-2010-11_VMS%20</td>
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<tr>
<td></td>
<td>Annual%20Report.pdf</td>
<td></td>
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<tr>
<td>Country</td>
<td>Region/Program</td>
<td>VMS Installation Percentage</td>
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<td>Cabo Verde</td>
<td>industrial fleet</td>
<td>71</td>
</tr>
<tr>
<td>Canada</td>
<td>CCAMLR, state-based programs</td>
<td>71</td>
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<tr>
<td>Cape Verde</td>
<td>partnership with EU</td>
<td>71</td>
</tr>
<tr>
<td>Country</td>
<td>Agency/Regulation</td>
<td>Number</td>
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<tr>
<td>--------------</td>
<td>--------------------------------------------------------</td>
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<td>Chile</td>
<td>CCAMLR, state-based programs</td>
<td>456</td>
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<td>China</td>
<td>IOTC, WFPFC, CCAMLR</td>
<td>60,000</td>
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<td>Cook Islands</td>
<td>Pacific Islands Forum Fisheries Agency (FFA), CCAMLR</td>
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<tr>
<td>Croatia</td>
<td>EU Regulation</td>
<td>256</td>
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<td>Cuba</td>
<td>Northwest Atlantic Fisheries Organization, Bilateral agreement with Mexico</td>
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<td>Cyprus</td>
<td>EU Regulation</td>
<td>19</td>
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<td>Denmark</td>
<td>EU Regulation</td>
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<td>Country</td>
<td>Organization</td>
<td>MMSI</td>
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<td>Egypt</td>
<td>ICCAT</td>
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<td>Faeroe Islands</td>
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<tr>
<td>Country</td>
<td>Program/Monitoring System</td>
<td>Vessels/Program Details</td>
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<tr>
<td>French Guiana</td>
<td>Kenya Coastal Development Project pdf</td>
<td>[Link](<a href="https://www.google.com/url?sa=t&amp;rct=j&amp;q=&amp;esrc=s&amp;source=web&amp;cd=6&amp;ved=0ahUKEwjF6__o46jZAhvVCc98KHXoSAoWQfgaMAU&amp;url=http%3A%2F%2Fiwlearn.net%2Fresolv">https://www.google.com/url?sa=t&amp;rct=j&amp;q=&amp;esrc=s&amp;source=web&amp;cd=6&amp;ved=0ahUKEwjF6__o46jZAhvVCc98KHXoSAoWQfgaMAU&amp;url=http%3A%2F%2Fiwlearn.net%2Fresolv</a> uid%2Fvd7F5c4e679e37Ff29a886169e6b893f&amp;usg=AOvVaw2EjjaLTN7cKvvt0d0JP_a0)</td>
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<tr>
<td>Gabon</td>
<td>industrial fleet</td>
<td><a href="https://www.researchgate.net/profile/Pierre_Failler/publication/289460422_Background_document_Workshop_on_Monitoring_Control_and_Surveillance_an_effective_tool_to_fight_against_IUU_fishing/links/568ce3fb08ae153299b7ac23/Background_document-Workshop-on-Monitoring-Control-and-Surveillance-an-effective-tool-to-fight-against-IUU-fishing.pdf">Link</a></td>
</tr>
<tr>
<td>Gambia</td>
<td>Presentation by Robert Gallagher, Consultant to the FAO: <a href="http://www.oceandocs.org/bitstream/1834/328/2/Pages%20from%20FAO%201-103-2.pdf">Link</a></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>EU Regulation, CCAMLR</td>
<td>Uses vTrack; <a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">Link</a></td>
</tr>
<tr>
<td>Ghana</td>
<td>WARFP</td>
<td>VMS to cover all industrial vessels; <a href="http://www.spcsrp.org/en/warfp-ghana">Link</a></td>
</tr>
<tr>
<td>Greece</td>
<td>CCAMLR, EU</td>
<td>550 uses vTrack; <a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">Link</a></td>
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<tr>
<td>Greenland</td>
<td>NAFO</td>
<td>100 vTrack; bilateral agreement with Iceland; <a href="http://www.fao.org/fishery/topic/18085/en">Link</a></td>
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<tr>
<td>Guinea</td>
<td>WARFP</td>
<td>&quot;Report of the Sub-Regional Fisheries Commission Workshop on Vessel...&quot;</td>
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<table>
<thead>
<tr>
<th>Country</th>
<th>System(s)</th>
<th>Description</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Iceland</td>
<td>EU Regulation</td>
<td>1608 All Icelandic fisheries, anglers, multipurpose, stern trawlers</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
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<tr>
<td>India</td>
<td>CCAMLR</td>
<td>Argos</td>
<td><a href="http://www.fao.org/fishery/countryprofiles/search/en">http://www.fao.org/fishery/countryprofiles/search/en</a></td>
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<tr>
<td>Iran</td>
<td></td>
<td>introduced VMS to assist in monitoring industrial fisheries; all demersal trawl vessels</td>
<td>FAO 2000; “Review of the State of WorldCapture Fisheries Management” Issue 488</td>
</tr>
<tr>
<td>Ireland</td>
<td>EU Regulation</td>
<td>213 Irish Naval Service Fisheries Monitoring Centre</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
</tr>
<tr>
<td>Italy</td>
<td>CCAMLR, South Pacific, EU</td>
<td>1608 groundfish fisheries monitoring agreement with Japan, Russia, South Korea, and US</td>
<td><a href="http://www.suisankai.or.jp/topics_e/isaribi/isaribi_53.pdf">http://www.suisankai.or.jp/topics_e/isaribi/isaribi_53.pdf</a></td>
</tr>
<tr>
<td>Japan</td>
<td>SEAFO, CCAMLR</td>
<td>mandatory for every fishing vessel</td>
<td>FAO 2000; “Review of the State of WorldCapture Fisheries Management” Issue 488</td>
</tr>
<tr>
<td>Country</td>
<td>Organization/Agreement</td>
<td>VMS Technology</td>
<td>Link</td>
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</tr>
<tr>
<td>Latvia</td>
<td>EU Regulation</td>
<td>69</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
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<td>Lithuania</td>
<td>EU Regulation</td>
<td>50</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
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<tr>
<td>Madagascar</td>
<td></td>
<td></td>
<td>“Review of the State of World Marine Capture Fisheries Management” Issue 488</td>
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<td>Maldives</td>
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<td>“Review of the State of World Marine Capture Fisheries Management” Issue 488</td>
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<td>Malta</td>
<td>EU Regulation</td>
<td>60</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
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<tr>
<td>Mauritius</td>
<td>CCAMLR</td>
<td></td>
<td>FAO 2000; “Review of the State of World Marine Capture Fisheries Management” Issue 488</td>
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<tr>
<td>Mexico</td>
<td>Bilateral agreement between mexico and cuba</td>
<td>2042</td>
<td>OECD Review</td>
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Morocco

| 300 | BlueFinger Ltd, industrial vessels | https://books.google.com/books?id=FbPWoc
0pwwjC&pg=PA94&lpg =PA94&dq=Argentina +VMS+fisheries&sourc e=bl&ots=kDCJGGuR
9&sig=B1hzgFWbfPSKb EcZTF2qwFISDyB0&hl =en&sa=X&ved=0ahU KEwis8v-
to6bZAhVuTd8KHZafD llQ6AEIIZTAI#v=onepa ge&q=Argentina%20VMS%20fisheries&f=fa ,
https://www.research
gate.net/profile/Piere_Failler/publication/
289460422_Background_Workhop_on_Monitoring_Control_and_Surveillance_an_effective_tool_to_fight_against_IUU_fishing.pdf

Mozambique

| nation wide implementation in 2004 (industrial, shrimp swallow water, deep shrimp, line fish) commercial offshore, coastal inshore artisanal | Review of the State of World Marine Capture Fisheries Management Issue 488

Myanmar

| SEAFO, CCAMLR | "Review of the State of World Marine Capture Fisheries Management Issue" 488

Namibia

| EU funded MCS program for SADC region, industrial | https://www.research
gate.net/profile/Piere_Failler/publication/
289460422_Background_Workhop_on_Monitoring_Control_and_Surveillance_an_effective_tool_to_fight_against_IUU_fishing.pdf

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<th>Program/Regulation</th>
<th>Number</th>
<th>Method</th>
<th>Website/Reference</th>
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<tr>
<td>Nauru</td>
<td>PNA; Pacific Islands Forum Fisheries Agency (FFA)</td>
<td>all foreign vessels licensed to fish/support fishing ops in Nauru waters; Pacific Islands Forum Fisheries Agency</td>
<td><a href="http://license.ffa.int/">http://license.ffa.int/</a></td>
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<tr>
<td>Netherlands</td>
<td>EU Regulation, CCAMLR</td>
<td>500</td>
<td>nationwide, vTrack</td>
<td><a href="http://www.fisherysolution.com/">http://www.fisherysolution.com/</a></td>
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<td>Nicaragua</td>
<td>By law, all vessels must have VMS installed.</td>
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<td>“STUDY ON FISHERIES CRIME IN THE WEST AFRICAN COASTAL REGION 2014”</td>
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<tr>
<td>Nigeria</td>
<td>By law, all vessels must have VMS installed.</td>
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<td><a href="http://www.fao.org/fishery/topic/18074/en">http://www.fao.org/fishery/topic/18074/en</a></td>
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<tr>
<td>Oman</td>
<td>Introduced VMS to assist in monitoring industrial fisheries</td>
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**Effective tool to fight against IUU fishing.pdf**
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<tr>
<th>Country</th>
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<th>Fishing Gear</th>
<th>Implementation Method</th>
<th>Related Links</th>
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<td>Pacific Islands</td>
<td>Parties to the Nauru Agreement (PNA)</td>
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<td>Tuna purse seine (PNA)</td>
<td><a href="https://www.pnatuna.com/content/1st-pna-implementing-arrangement">https://www.pnatuna.com/content/1st-pna-implementing-arrangement</a> “Review of the State of World Marine Capture Fisheries Management” Issue 488</td>
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<td>Pakistan</td>
<td>CCAMLR</td>
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<td>Demersal Industrial</td>
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<td>Philippines</td>
<td>ICCAT, IOTC, CCSBT, WCPFC</td>
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<td>Purse seine, longline, ring net, trawlers, other fishing gears and fish carriers and transshipment vessels</td>
<td><a href="https://www.bfar.dagov.ph/LAW?fi=404">https://www.bfar.dagov.ph/LAW?fi=404</a></td>
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<td>Poland</td>
<td>EU Regulation, CCAMLR</td>
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<td>Nationwide, vTrack</td>
<td><a href="http://www.fisherysolution.com/">http://www.fisherysolution.com/</a></td>
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<td>Portugal</td>
<td>EU Regulation</td>
<td>486</td>
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<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
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<td>Romania</td>
<td>EU Regulation</td>
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<td>Russia</td>
<td>CCAMLR</td>
<td>3800</td>
<td>Sectoral system for MCS over fishing vessels activities</td>
<td><a href="http://www.fao.org/fishery/topic/18090/en">http://www.fao.org/fishery/topic/18090/en</a></td>
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<td>Country</td>
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<td>Seychelles</td>
<td>SFA Fisheries Monitoring Centre, IOTC</td>
<td>tuna longline; All seychelles flagged vessels are required to report through VMS</td>
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<td>Sierra Leone</td>
<td>trawl fishery</td>
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<td><a href="https://books.google.com/books?id=FbPWoc0pwjIC&amp;pg=PA94&amp;lpg=PA94&amp;dq=Argentina+VMS+fishe">https://books.google.com/books?id=FbPWoc0pwjIC&amp;pg=PA94&amp;lpg=PA94&amp;dq=Argentina+VMS+fishe</a></td>
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<td>Slovenia</td>
<td>EU Regulation</td>
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<td><a href="http://www.fisherysolution.com/">http://www.fisherysolution.com/</a></td>
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<td>South Africa</td>
<td>SEAFO, state-based programm, CCAMLR</td>
<td>Marine and Coastal Management Org in Dept. of Env Affairs and Touris.; Hake trawl fishery; hake longliners</td>
<td><a href="http://www.fao.org/docrep/x3900e/x3900e08.htm#topofpage">http://www.fao.org/docrep/x3900e/x3900e08.htm#topofpage</a></td>
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<td>Vessels</td>
<td>Fishing Activities</td>
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<tr>
<td>South Pacific</td>
<td>South Pacific Forum Fisheries Agency (FFA)</td>
<td>1024</td>
<td>Longline, purse seine, pole and line, and support vessels</td>
<td><a href="http://www.fao.org/fishery/topic/18074/en">http://www.fao.org/fishery/topic/18074/en</a></td>
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<tr>
<td>Spain</td>
<td>EU Regulation, CCAMLR</td>
<td>2700</td>
<td>Legal framework = National and EU VMS regulations; Longline (deep and surface), Purse seine (fresh and frozen), Pole and line, Trawl (fresh and frozen), Gillnet</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
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<td>Sri Lanka</td>
<td>IOTC</td>
<td>450</td>
<td>offshore and high seas large pelagic fishing activities</td>
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<tr>
<td>Suriname</td>
<td>Ministry of Agriculture, Farming, and Fisheries; initially 80 Vessels; argos</td>
<td>20</td>
<td>Seabob shrimp fishery Onsite Surveillance Visit - Report for Suriname Atlantic Seabob Shrimp Fishery Report</td>
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<td>Sweden</td>
<td>EU Regulation, CCAMLR</td>
<td>184</td>
<td>nationwide; operated by Havs-och vattenmyndigheten (Marine and Water Management); all fishing vessels &gt;=12 m LoA</td>
<td><a href="https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en">https://ec.europa.eu/fisheries/cfp/control/technologies/vms_en</a></td>
<td></td>
</tr>
<tr>
<td>Taiwan Province of China</td>
<td>NA</td>
<td>855</td>
<td>longliners, purse seiners, squid jigging vessels, saury torch light vessels, fish carriers</td>
<td><a href="http://www.fao.org/fishery/topic/18082/en">http://www.fao.org/fishery/topic/18082/en</a></td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Region/Agency/Regulations</td>
<td>VMS AND AIS</td>
<td>Mandated Vessels</td>
<td>Coverage %</td>
<td>Vessel Monitoring System</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>------------------</td>
<td>------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Trinidad and Tobago</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunisia</td>
<td></td>
<td>62 Vessels have already been equipped with VMS with 900 to follow suit as of April 2015</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuvalu</td>
<td>Pacific Islands Forum</td>
<td>3</td>
<td></td>
<td></td>
<td>vtrack; trawl and longline vessels</td>
</tr>
<tr>
<td>Ukraine</td>
<td>NAFO, CCAMLR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>EU Regulation</td>
<td>938</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Uruguay state-based program, CCAMLR

Mandatory for all fishing vessels than is more than 10 gross registered tones (industrial fishing fleet); Continental shelf trawling for hake; coastal trawling for white croaker and sea trout; scallop fishery; clam fishery; flounder and volute fishery; deep sea red crab pot fishery; anchovy purse seine fishery; red fish trawler fishery; other trawling for croaker, cutlassfish and other percomorphs; squid jigging for argentine shortfin squid; pelagic longline for tunas, swordfish and pelagic shark; bottom longline for skate and rays, sea bass and wreckfish; toothfish longline for patagonian toothfish and antarctic toothfish; toothfish longline and pot fish for patagonian toothfish and antarctic toothfish; Hake on the continental shelf of the Uruguayan-Argentine CFZ; white croaker and sea trout fishing in the coastal zone in the La Plata River and U-A CFZ.

US - Northeast Region US State-based program

The Northeast Region includes marine waters off US states of Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland, Virginia, North Carolina; Scallop (dredge), Northeast multispecies (trawl, gillnet, hook gear),
<table>
<thead>
<tr>
<th>Region</th>
<th>US State-based program</th>
<th>Count</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>US - Northwest Region</td>
<td>US State-based program</td>
<td>297</td>
<td>Washington, Oregon, and California; Limited entry permitted vessels; Vessels that fish in a Rockfish Conservation Area (RCCA) with the following gear type: limited entry fixed gear; limited entry midwater trawl gear; limited entry bottom trawl gear;</td>
</tr>
<tr>
<td>US - Pacific Islands Region</td>
<td>US State-based program</td>
<td>200</td>
<td>US islands of Hawaii, Guam, Northern Mariana Islands, American Samoa, Wake Island, Midway Island, Howland and Baker Islands, Kingman Reef and Palmyra Atoll, Johnston Island and Jarvis Island; Pelagic longline; Northwestern Hawaiian Islands lobster trap; American Samoa alia (small vessel longline); Tuna purse seine (operating under South Pacific Tuna Treaty); Krill trawl (operating under CCAMLR); Foreign longline, pole and line (operating according to terms of court-ordered settlement agreements resulting from violations of US fishery law)</td>
</tr>
<tr>
<td>Area</td>
<td>Program Type</td>
<td>Number</td>
<td>Details</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------------------</td>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>US - Southeeast Region</td>
<td>US State-based program</td>
<td>269</td>
<td>North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Texas as well as US waters around Puerto Rico and the US Virgin Islands; Rock shrimp endorsement holders (trawl); HMS (pelagic longline); Shark (gillnet and bottom longline gear); Penalty fleet (vessels subject to VMS monitoring as a penalty for violating fisheries regulations)</td>
</tr>
<tr>
<td>US- Alaska Region</td>
<td>US State-based program</td>
<td></td>
<td>Pollock, Pacific Cod, Atka Mackerel (jig gear or dingle bar gear excluded); “operating in the Aleutian Island or in adjacent State of Alaska waters; federal reporting areas 610, 620, 630 and receives/processes groundfish from other vessels; Rockfish Program; Sablefish in the Bering Sea or Aleuitian Islands; Crab Rationalization Program</td>
</tr>
</tbody>
</table>
### III. Python Code: VMS Points to Lines ArcGIS tool

```python
import arcpy, sys, csv, os
from arcpy import env
from datetime import datetime
import numpy as np

#overwrite outputs
env.overwriteOutput = True

#User Selects Text File (.csv)
fileName = sys.argv[1]
fileObj = open(fileName, 'r')  # open csv
#read header
headerLine = fileObj.readline()
#move cursor to first row
lineString = fileObj.readline()

#User selects scratch folder for workspace
scratch = sys.argv[2]
env.workspace = scratch

#Create new csv to write into
ew_csv = "XYpoints.csv"  #csv file
csv_out = open(new_csv, 'wb')  #open new file

writer = csv.writer(csv_out)  #function to write into csv

#write in header, including a new field for "trip"
headerItems = headerLine.split(',')  #comma delimited
headerRow = headerItems[0:6]  #keep first 7 columns
newEnd = headerItems[6].strip('n')  #remove the end from the last column
headerRow.append(newEnd)  #append headers without 'n'
headerRow.append("Trip")  #add "trip" field
writer.writerow(headerRow)  #write headers into new csv

#starting Trip value
trip = 1

while lineString:
    lineItems = lineString.split(',')  #split line by command
    Date = lineItems[0]  #start date value
    newdate1 = datetime.strptime(Date, "%m/%d/%Y")  #convert to datetime format in month/day/year
    Edate = lineItems[1]  #end date
    newdate2 = datetime.strptime(Edate, "%m/%d/%Y")  #convert to datetime format in month/day/year
    deltaT = newdate2 - newdate1  #find difference between end date and start date
    if deltaT.days < 2:  #if the difference is less than 2 days
        mem = trip  #assign trip value
        lineItems.append(mem)  #append current row with trip value
        writer.writerow(lineItems)  #write row into the new data file, including new trip value
    lineString = fileObj.readline()  #move to next line
```

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else:
    trip = trip + 1  # if difference is 2 days or more, start new "trip"
    mem = trip  # assign trip value
    #DO NOT WRITE THIS POINT INTO NEW CSV - end of this "track"
    lineString = fileObj.readline()  # move onto next row

#Close input file
fileObj.close()
#Close output file
csv_out.close()

###PANDAS
import pandas as pd
df = pd.read_csv("XYpoints.csv")  # read newly created csv into pandas
table = pd.pivot_table(df, values=df.columns[-2], index=df.columns[1],
aggfunc=np.mean)  # create pivot table to find average speed for each trip
table.to_csv("speed.csv")  # write pivot table into new csv

# ADD HEADER TO AVERAGE SPEED CSV (currently contains no header - need
# header to join fields later)
fileName = "speed.csv"
fileObj = open(fileName, 'r')  # open average speed csv to read
lineString = fileObj.readline()  # move cursor to first row
new_csv = "avg_speed_K.csv"  # create new csv to write speeds into based on
trip number
csv_out = open(new_csv, 'wb')  # open new csv to write into
# function to write into csv
writer = csv.writer(csv_out)
headerRow = ["Trip", "Avg_Knots"]  # dictate new header row
writer.writerow(headerRow)  # write header row into new csv
while lineString:
    lineItems = lineString.split(',')  # comma delimited
    writer.writerow(lineItems)  # write row into new csv
    lineString = fileObj.readline()  # move to next line

#Close input file
fileObj.close()
#Close output file
csv_out.close()

# Pandas group by to find start and end date of each trip
g = df.groupby('Trip')  # group the points by the Trip value assigned above
gStart = g.nth(1)  # find the Starting Date for each trip
gEnd = g.nth(-1)  # find the Ending Date for each trip
gStart.to_csv("StartDate.csv")  # convert grouped start date panda df to csv
gEnd.to_csv("EndDate.csv")  # convert grouped end date panda df to csv

# Remove all fields from csv except for Trip value and Start Date
fileName = "StartDate.csv"  # start date csv
fileObj = open(fileName, 'r')  # open csv
# move cursor to first row
lineString = fileObj.readline()
lineString = fileObj.readline()

new_csv = "S_Date.csv" # new csv to write into
csv_out = open(new_csv, 'wb') # open new csv
# function to write into csv
writer = csv.writer(csv_out)
headerRow = ["Trip", "Start_Date"] # dictate new headers for new csv
writer.writerow(headerRow) # write headers into csv

while lineString:
    lineItems = lineString.split('\n',) # comma delimited
    lineItems = lineItems[0], lineItems[1] # keep only trip field and starting date field
    writer.writerow(lineItems) # write into the new csv
    lineString = fileObj.readline() # move to next row

# close input file
fileObj.close()
# close output file
csv_out.close()

# Remove all fields from csv except for Trip value and End Date
fileName = "EndDate.csv" # csv just created from pandas group by function
fileObject = open(fileName, 'r') # open csv
# move cursor to first row
lineString = fileObj.readline()
lineString = fileObj.readline()
# lineString = fileObj.readline()

new_csv = "E_Date.csv" # new csv to write into
csv_out = open(new_csv, 'wb') # open new csv
# function to write into csv
writer = csv.writer(csv_out)
headerRow = ["Trip", "End_Date"] # dictate new headers
writer.writerow(headerRow) # write in new headers

while lineString:
    lineItems = lineString.split(\n',\') # comma delimited
    lineItems = lineItems[0], lineItems[2] # keep only trip field and end date field
    writer.writerow(lineItems) # write row into new csv
    lineString = fileObj.readline() # move to next line

# close input file
fileObj.close()
# close output file
csv_out.close()

#MERGE newly modified csvs using Pandas
a = pd.read_csv("avg_speed_K.csv") # read in first csv
b = pd.read_csv("S_Date.csv") # read in second csv
b = b.dropna(axis=1)
merged = a.merge(b, on='Trip') # merge panda dataframes by "trip" field
merged.to_csv("output.csv", index=False) # output
a = pd.read_csv("output.csv")  # read in output from above
b = pd.read_csv("E_Date.csv")  # read in third csv
b = b.dropna(axis=1)
merged = a.merge(b, on='Trip')  # merge panda data frames by "trip" field
merged.to_csv("AttributesToJoin.csv", index=False)  # output includes the
attributes I want to join to final line feature class

#CSV TO SPATIAL POINT SHAPEFILE
in_Table = "XYpoints.csv"  # csv with Trip values created above
x_coords = "Lon"
y_coords = "Lat"
out_Layer = "VesselPoints_layer"  # name of layer from XY data
spRef = sys.argv[3]  # User defined spatial reference (WGS84 for Sierra
Leone data)
arcpy.MakeXYEventLayer_management(in_Table, x_coords, y_coords, out_Layer, spRef)  # make the layer
arcpy.SaveToLayerFile_management(out_Layer, saved_Layer)  # make the layer
permanent

## copy
in_features = "points.lyr"  # layer from above
out_features = "VesselPoints.shp"  # points shapefile name
arcpy.CopyFeatures_management(in_features, out_features)  # make permanent
points shapefile

###MAKE LINES FROM POINTS, GROUPED BY TRIPS

in_table = "AttributesToJoin.csv"  # Convert csv file with attributes to a DBF table in order to join to
polyline file
arcpy.MakeTableView_management("AttributesToJoin.csv", "AttributesToJoin")
# make csv into table view
arcpy.CopyRows_management("AttributesToJoin", "AttributesToJoin.dbf")  # save table view as dbf

### point to line
in_features = out_features  # Vessel points shapefile created above
out_features = sys.argv[4]  # user defined output feature class for
polylines
lineField = "Trip"  # lines are grouped by trips
sortField = "Date"  # ordered consecutively by date
arcpy.PointsToLine_management(in_features, out_features, lineField, sortField)  # execute point to lines

# Join dates to Lines
in_data = out_features  # line feature class created above
in_field = "Trip"  # line feature class join field = "Trip"
join_table = "AttributesToJoin.dbf"  # attributes DBF created above
join_field = "Trip"  # join table join field = "Trip"
field_list = ["Avg_Knots", "Start_Date", "End_Date"]  # keep only avg_knots,
start_date, and end_date from join table
arcpy.JoinField_management(in_data, in_field, join_table, join_field, field_list)  # execute join
IV. Python Code: Separate vessel VMS tracks into individual “Ids”

```python
#open CSV
import arcpy, sys, csv, os
from arcpy import env
import datetime
from datetime import datetime
import time
from datetime import timedelta
import numpy as np

#overwrite outputs
env.overwriteOutput = True

# Text File (.csv)
fileName = "X:\hb101_FinalProject\Archive\ReadyForTool\VMS.csv"
fileObj = open(fileName, 'r') #open csv
#read header
headerLine = fileObj.readline()
#move cursor to first row
lineString = fileObj.readline()

#scratch folder for workspace
scratch = "X:\hb101_FinalProject\hb101_FinalProject\scratch"
env.worksp
ace = scratch

#Create new csv to write into
name = "X:\hb101_FinalProject\hb101_FinalProject\OutputFromTool\vessel_output"
new_csv = name + '.csv'
csv_out = open(new_csv, 'wb') #open new file
writer = csv.writer(csv_out) #function to write into csv

#write in header, including a new field for "trip"
headerItems = headerLine.split(','.__) #comma delimited
headerRow = headerItems[0:4] #keep first 7 columns
newEnd = headerItems[4].strip('n') #remove the end from the last column
headerRow.append(newEnd) #append headers without '
'
headerRow.append("Id") #add "trip" field
writer.writerow(headerRow) #write headers into new csv

#starting Trip value
trip = 1

while lineString:
    lineItems = lineString.split(','.__) #split line by command
    Date = lineItems[0] #start date value
    newdate1 = datetime.strptime(Date, "%m/%d/%Y %H:%M:%S") #convert to
datetime format in month/day/year hours:minutes:seconds
    Edate = lineItems[1] #end date
    newdate2 = datetime.strptime(Edate, "%m/%d/%Y %H:%M:%S") #convert to
datetime format in month/day/year hours:minutes:seconds
    deltaT = newdate2 - newdate1 #find difference between end date and start
date
```

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print deltaT
#newTime = time.gmtime(deltaT)
timeCompare = timedelta(hours = 8)
print timeCompare
if deltaT < timeCompare:  #if the difference is less than 8 hours
    mem = trip  #assign trip value
    lineItems.append(mem)  #append current row with trip value
    writer.writerow(lineItems)  #write row into the new data file,
    including new trip value
    lineString = fileObj.readline()  #move to next line
else:
    trip = trip + 1  #if difference is 2 days or more, start new "trip"
    mem = trip  #assign trip value
    lineItems.append(mem)  #append current row with trip value
    writer.writerow(lineItems)  #write row into the new data file,
    including new trip value
    lineString = fileObj.readline()  #move onto next row

#Close input file
fileObj.close()
#close output file
csv_out.close()
V. Python Code: Interpolate VMS tracks into consistent time series

```python
#load packages
from pandas import read_csv
from pandas import datetime
from matplotlib import pyplot
import pandas as pd
import os, sys
import glob

#read in directory
path = 'C:\Users\hb101\Downloads\OutputFromTool\OutputFromTool\'
#for loop through each csv file in directory
for infile in glob.glob(os.path.join(path, '*.csv')):
    name = os.path.basename(infile.strip('output.csv'))
    #name of file = basename only, not path
    #format date/time steps to make real dates and times
    def parser(x):
        return datetime.strptime(x, '%m/%d/%Y %H:%M')
    #read in VMS points from individual vessel, calling date/time function from above
    vessel = read_csv(infile, header=0, parse_dates=[0], index_col=0, squeeze=True, date_parser=parser)
    #create empty data frame
    df = pd.DataFrame(columns=['x', 'y', 'Speed_in_K', 'Id'])
    #create starting index
    start = 1
    #subset vessel data frame by Id (i.e. "trips")
    trips = vessel[vessel['Id'] == start]
    #loop through Ids
    while (len(trips)>1):
        upsampled = trips.resample('H') #upsample to create standard array of time (one observation per hour)
        wIndex = upsampled.reset_index(drop=True) #re-index
        interpolated = wIndex.interpolate(method='linear', spline=True)
        #interpolate x,y points and speed
        data = pd.DataFrame(interpolated) #save in temporary data frame to add to df
        df = data.append(df) #append df
        start = start + 1 #move to next Id value
        trips = vessel[vessel['Id'] == start] #subset next Id
        while (len(trips)<1):
            break #stop loop when max Ids are reached
    df.to_csv('C:\Users\hb101\Downloads\interpolated' + str(name) + 'interpolated.csv') #create unique csv file based on name
```