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Improving area swept estimates from bottom trawl surveys☆

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ABSTRACT

Estimation of area swept is a key component for standardizing catch per unit effort (CPUE) data from fishery independent bottom trawl surveys and survey trawl gear experiments. Given technological advances and the proliferation of data streams from net mensuration equipment and global positioning system (GPS), techniques for estimating survey effort can be improved. Here we investigate new analytical techniques for improving the accuracy and precision of survey effort estimation. Sources of error and bias associated with two of the components used to compute area swept as a measure of fishing effort, distance fished by the trawl and net spread, are systematically examined and their influence quantified using both simulated and survey data. New analytical methods, a cubic spline smoothing algorithm to smooth GPS and net spread data, a haversine great circle algorithm to calculate distance between smoothed GPS track points, and a sequential outlier rejection algorithm to diminish the influence of noise on mean net spread estimates are shown to reduce or even eliminate the influence of biased observations on area swept estimators.

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1. Introduction

Fishery-independent trawl surveys provide vital information for fish stock assessment and management in many countries throughout the world. Abundance estimates based on results from these surveys are considered to be more reliable than those derived strictly from commercial fisheries data because survey effort and trawl catchability can be controlled through standardization (e.g., Stauffer, 2004) to minimize variability of these two parameters in time and space. The problem of both spatial or temporal changes in catchability that result in bias leading to errors in stock assessment and management and its ramifications have been well studied (e.g., Beverton and Holt, 1957; Byrne et al., 1981; Collie and Sissenwine, 1983; Pennington, 1986; Swain et al., 1994; Pennington and Godø, 1995). However, the analogous problem of spatial or temporal variability in the error associated with fishing effort estimation has surprisingly received little attention (e.g., Gould et al., 1997), although this bias is often combined or confounded with changes in catchability.

Technological advances have allowed for greater precision in the estimation of effort in trawl surveys over time. For instance, fishing time (e.g., catch/hour) is often used as a standard unit of effort, but even relatively small differences in mean vessel speed over the sampling period can produce large changes in the sampled area or catch rates (Alderstein and Ehrich, 2002). The advent of more accurate and precise positioning methods (i.e., GPS) allows better estimates of the distance traveled by the net during the sampling period (distance fished) and many surveys currently use distance as the standard unit of effort. The development of acoustic net mensuration systems now allows continuous monitoring and recording of net spread throughout the tow (ICES, 2009), which in tandem with distance fished can be used to calculate area swept (distance fished × net spread) allowing a much more accurate, precise, and unbiased estimator of standard fishing effort. This study focuses on the development of methods to more accurately and precisely estimate components of survey effort that may reduce some of the variability of bottom trawl survey area swept estimates. This is done by systematically evaluating the methods currently being used at the U.S. National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center (AFSC), to screen data coming from survey instrumentation, in addition to examining the analytical procedures used to compute area swept as latent sources of bias. Although we use only data from the AFSC surveys, the methods presented here should be applicable to other bottom trawl surveys around the world that use area swept estimates of effort derived from GPS and acoustic net mensuration equipment.

A known source of error in the estimation of distance fished is the noise inherent in the GPS system. GPS noise results from atmospheric conditions, measurement noise, ephemeris errors (the difference between actual and expected orbital position of a GPS satellite), clock drift, or multipath errors (error resulting from a

Abbreviations: GPS, global positioning system; CPUE, catch per unit effort; AFSC, Alaska Fisheries Science Center; NMFS, National Marine Fishery Service; SOR, sequential outlier rejection; MSE, mean squared error.

☆ The findings and conclusions in the paper are those of the authors and do not necessarily represent the views of the National Marine Fisheries Service.

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signal that rebounds from a local obstruction before being received by the GPS unit; Hofmann-Wellenhof et al., 1997), hence each position along a tow path is subject to estimation error. Additional systematic sources of error can also result from GPS antenna motion caused by the pitch and roll of the vessel. A popular approach to reducing the effect of these types of error has been to reduce the polling frequency of positional information (Palmer, 2008). As polling frequency decreases, the error in distance fished as a fraction of the total distance fished decreases. Some surveys decrease polling frequency to the lowest rate possible and calculate the distance fished as a straight line between the start and end positions of the tow (e.g., Stauffer, 2004). However, low polling frequency can result in large underestimation of distance fished when tow paths are sinuous (Palmer, 2008). Another approach has been to smooth GPS data before the application of a distance algorithm in an attempt to describe the true tow path after noise removal. Several different smoothing algorithms have been applied to GPS data from trawl surveys, including simple exponential smoothing and moving average type smoothers (Stauffer, 2004).

Bias can also result from the algorithm used to estimate the distance fished along a smoothed tow path. Most surveys have employed a variant of either a great circle (Vincenty, 1975) or a Euclidean (Stauffer, 2004) distance estimator. Some implementations of the great circle estimator are inaccurate when estimating very small distances due to rounding errors introduced through the underlying trigonometric functions (Snyder, 1987). The Euclidean method of estimating distance underestimates the path length over long distances on the Earth's surface, since it assumes a planar system and yields the length of the chord bounding the segment whose arc (the distance traveled) connects the chord's endpoints. This estimation error is likely quite small over the short distance covered by a typical survey tow (ca. 1–3 km). Euclidean estimators can also be inaccurate over short distances if the assumed ellipsoidal model of the earth's surface is incorrect.

The accuracy of net spread observations from net mensuration systems are affected by several factors. Sound sources other than the two transducers that produce sound at or near the specified transmission frequencies can result in incorrect readings. Although the beam angles of these systems are typically quite large, misalignment of the transducers can lead to indirect path signals resulting in overestimation of the distance between the transducers. Any movement of the sensors independent of the movement of the net or doors can also result in measurement error. The most common net mensuration systems estimate the distance between transducers by converting the time between sending and receiving a signal into distance, assuming a constant sound speed of 1500 m s^{-1}. However, sound speed is not constant and varies with water temperature, pressure, and salinity. Therefore errors also can occur in the calculation of mean spread estimates when surveys sample over variable environmental conditions. Mean net spread estimates for a tow are often calculated by first eliminating spurious observations, typically rejecting values outside an acceptable range, and calculating a mean from the remaining spread values (ICES, 2009). We will refer to this method as gating (or using fixed gates) in the remainder of this manuscript. If accurate spread measurements are excluded or inaccurate spread measurements are included, biased estimates will result.

2. Material and methods

2.1. Distance fished

We considered two components of estimation of over ground distance fished: the data smoother and the algorithm to estimate distance from the smoothed points. Four smoothing algorithms were evaluated: a moving average smoother; simple exponential smoothing (Brown and Meyer, 1961); Friedman's super smoother (Friedman, 1984); and the cubic spline (Hastie and Tibshirani, 1990). A series of simulations were undertaken to evaluate the relative performance of each smoother. Each simulation consisted of first constructing a tow path with a total distance traveled of 2.778 km (1.5 nm) simulating GPS data collected at 2 s intervals for 30 min at a speed of three knots. The course along the tow path was changed at each observation by randomly choosing a course change from a range of allowed values at the given sinuosity level. As the sinuosity level increased, the range of course change allowed between consecutive observations increased, thereby increasing the sinuosity of the tow path. The result was then considered the 'known' tow path. Random noise was added to the known tow path by randomly choosing a distance from a normal distribution with a standard deviation equal to the pre-selected noise level and then randomly choosing a direction from the known observation. The 'observed' position was then calculated using the distance and direction from the known position. Each smoother was then applied to the simulated GPS data and a distance was calculated for the smoothed tow path. Since each smoother investigated has some sort of smoothing parameter mechanism to control overall smoothness, each smoother was investigated at several smoothness levels which we hereafter refer to as span. Five hundred simulations were conducted at each of six noise levels (1, 5, 10, 15, 25, 50), six sinuosity levels (0.05, 1, 2.5, 5, 7.5, 10), and seven span levels (4, 6, 8, 10, 15, 30, and 60; Fig. 1).

The running mean smoother used mimicked the smoother currently used to smooth GPS data from AFSC surveys. The latitude and longitude of each smoothed position was estimated as the mean of the latitudes and longitudes of the current point and span level $\times 2^{-1}$ points both before and after the current point. For simple exponential smoothing, the smoothing parameter α was set at $2 \times (\text{span}+1)^{-1}$. We used the 'supsmu' function in R to implement the super smoother, using a span of span $\times$ (total number of GPS observations)$^{-1}$. We used the 'smooth spline' function in R (version 2.11.1, R Development Core Team (2010)) to implement the cubic spline algorithm, setting the number of knots argument ($n$knots) to (total number of GPS observations)$\cdot$span^{-1}. Although the spans are not completely analogous among the smoothers due to their different methodologies, we hoped that the inclusion of this parameter would give us some insight into the tradeoffs between the ability to accurately measure distance while the vessel is changing course and eliciting the true vessel path in the presence of large amounts of noise. The mean and variance of the differences between estimated and known tow path lengths were examined to evaluate each smoother's robustness to random noise and changes in course (i.e., sinuosity).

The distance algorithm used was an implementation of the haversine great-circle algorithm (Sinnott, 1984) correcting for the oblate spheroid of the earth. This algorithm was chosen because of its ability to accurately estimate distance even for points in very close proximity (i.e., <1 m apart). Some great circle algorithms commonly used to calculate distance do not perform well at small distances due to rounding errors incurred in the underlying inverse cosine function. The haversine algorithm avoids the inverse cosine function and therefore allows much more accurate estimation of small distances.

2.2. Net spread

Two aspects of net spread estimation were considered. First, simulated net spread data were used to develop a robust method of estimating mean spread using iterative sequential outlier rejection (SOR) and smoothing. Second, survey observations of temperature and depth were used to estimate sound speed on a tow-by-tow