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Measuring speed of vessels operating around endangered southern resident killer whales (*Orcinus orca*) in Salish Sea critical habitat

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ABSTRACT

Motorized vessels are a major source of anthropogenic noise and can have adverse effects on species relying on sound for communication and feeding. Monitoring noise levels received by endangered southern resident killer whales (SRKWs) requires knowing the number, distance, and speed of surrounding vessels, including small boats that do not have Automatic Identification Systems (AIS). A method for estimating their speed is required to predict received noise levels and compliance with vessel regulations. We compared theodolite and photogrammetry methods to estimate the number, distance, and speed of vessels in SRKW Salish Sea summertime critical habitat. By treating AIS as "truth", we found photogrammetry-derived ranges and speeds were more variable than theodolite estimates. Error in photogrammetry-derived speeds increased with range. Overall, we found time saved in the field using photogrammetry was more than offset by long analysis time. Theodolite data were relatively easy to collect, and produced accurate and precise results.

1. Introduction

Anthropogenic noise from vessel traffic, particularly in coastal habitats where small boats are concentrated (Magnier and Gervaise, 2020), can have deleterious effects on marine animals that rely on vocalizing and hearing to communicate and find prey (Erbe, 2002; Williams et al., 2014a; Tougaard et al., 2015; Wisniewska et al., 2018). Chronic noise from boats and ships can carry population-level consequences for many endangered whales and dolphins (Williams et al., 2020). Common methods for monitoring vessel activity, and collecting data for impact assessments include aerial surveys (Clark et al., 2010; Nichol et al., 2017), behavioural observations (Nowacek et al., 2001; Williams et al., 2009) land-based theodolite tracking (Würsig and Würsig, 1980; Williams et al., 2014b; Piwetz et al., 2018; Sullivan and Torres, 2018), and acoustic modeling (Erbe et al., 2014; Veirs et al., 2016). Sound field models frequently use a combination of sound-level measurements obtained from acoustics and ship traffic logs or Automatic Identification System (AIS) data to estimate noise levels from shipping activity through predictive modeling (Erbe et al., 2012; Hermannsen et al., 2019). In 2004, the International Maritime Organization (IMO) updated their regulations for AIS, requiring vessels 300 gross tonnage or more, cargo ships 500 gross tonnage or more, and passenger ships to have AIS operating on board (International Maritime Organization (IMO), 2004 https://www.imo.org/en/OurWork/Safety/Pages/AIS.aspx). In the US, commercial vessels over 65 ft in length are required to have AIS (Title 33, Part 164.46, Code of Federal Regulations). While AIS is an increasingly useful tool for modeling ship noise, small vessels are often left out of sound models which underestimates their contribution to the soundscape (Hermannsen et al., 2019).

The Salish Sea is a productive and biodiverse inland sea within Canada and the US (Flower, 2021). This region is home to a variety of marine mammal species, including the critically endangered southern resident killer whale (SRKW) (Gaydos and Pearson, 2011). Haro Strait, which is part of SRKW core summer foraging habitat (Fig. 1) (Ashe et al., 2010), is also one of the busiest international seaways in the Pacific, transecting the region and providing access to major ports of Vancouver and Seattle (Gillespie, 2016; Cominelli et al., 2018). This area is also one of the premier recreational boating and whale watching destinations in

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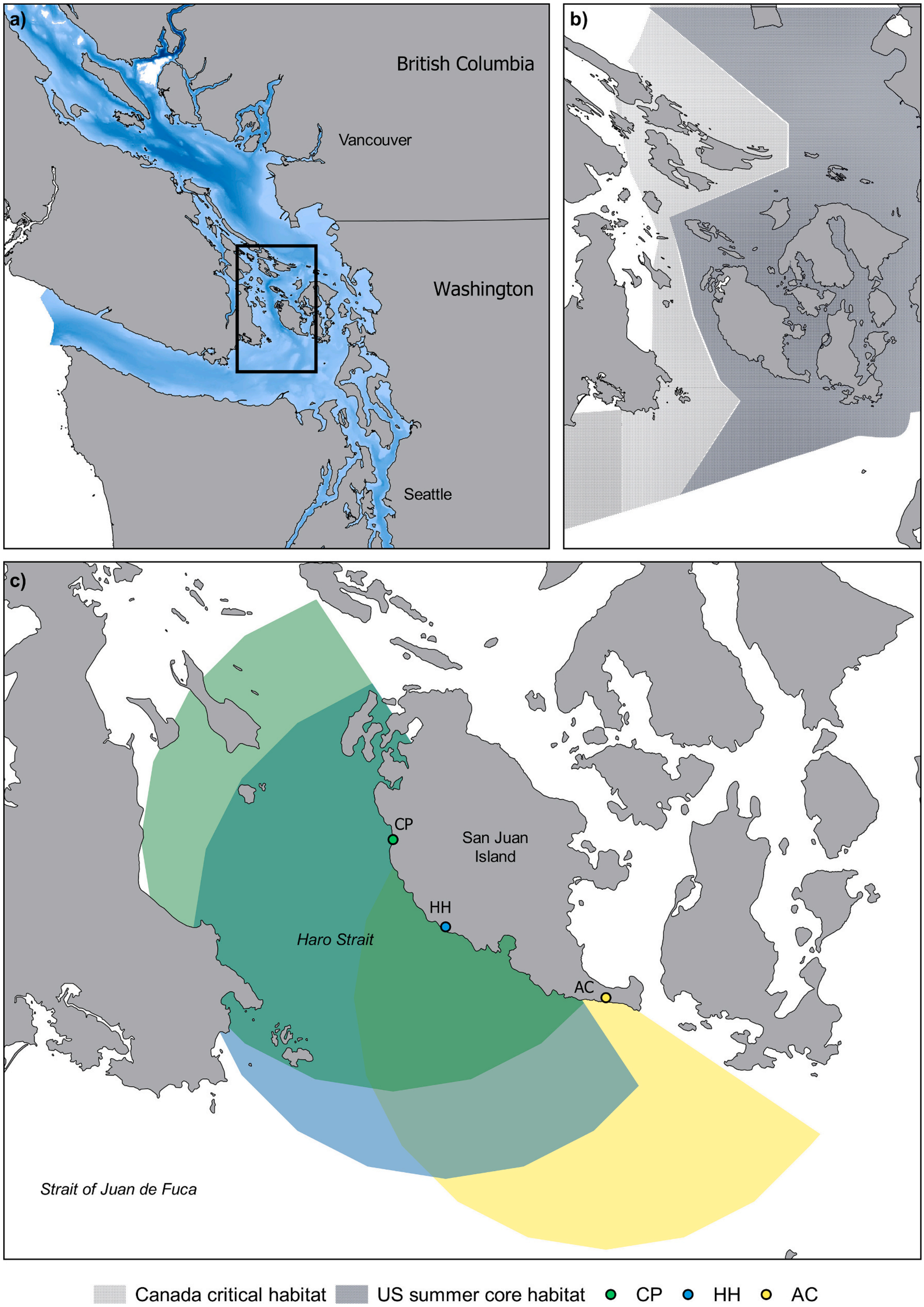

Fig. 1. a) The Salish Sea, bordered by British Columbia, Canada and Washington, USA (bathymetry data from Flower, 2021); b) transboundary protected areas: Critical Habitat of Species at Risk for SRKWs in Canadian waters (light hashing), SRKW Summer Core Area Critical Habitat in US waters (dark hashing); c) observer locations along the west side of San Juan Island overlooking Haro Strait and the Strait of Juan de Fuca: County Park (CP), Hannah Heights (HH), American Camp (AC). Semi-circles represent the site-specific boundaries used to filter AIS vessels >15 km away from observers as previously determined under the Slowdown Trial (Wood et al., 2018).

the US, which highlights the need to understand the impacts of all vessel types to support effective management regulations. A range of regulatory and voluntary guidelines have been established throughout the transboundary region to reduce the impacts of vessels on SRKWs. Precautionary vessel management regulation is in flux in both countries. At the time of this study, vessels in Washington State inland waters were required by law to maintain minimum distances of 300 yds. on either side of SRKWs and at least 400 yds. behind or in front of the whales' path, in addition to slowing to 7 knots or less within 0.5 nm of SRKWs. In Canadian waters, the law requires vessels to maintain a distance of 400 m in SRKW critical habitat and 200 m elsewhere, but only provides a voluntary guideline of slowing to 7 knots when within 1000 m of SRKWs. Additional measures include the ship slow-down from the Port of Vancouver, voluntary and mandatory no-go zones, and adjustments to recreational and commercial fishing activity (National Marine Fisheries Service (NMFS), 2011; Government of Canada, 2020; Be Whale Wise, 2021).

Effective management of vessel noise and mitigation of negative impacts on vocalizing species in the Salish Sea requires that sound models consider non-AIS-equipped vessels as a component of the soundscape. Bain et al. (2014) modeled changes in echolocation range with changes in received noise level to illustrate the importance of noise to prey detection. Due to the logarithmic perception of sound, received noise level is driven primarily by the loudest received noise, which may not necessarily be the closest sound source (Houghton et al., 2015). Received noise levels are a function of source level and distance from the source, vessel type, and speed. A slow, small boat traveling close by may be the least significant noise source when present with a more distant, faster, small boat or ship. The more distant, faster, small boat may be an intermediate noise source when a ship is present. Thus, estimation of the sound field requires identifying vessel type, speed of travel (together providing source level), and distance from the whales (providing transmission loss). While previous studies have investigated the role of shipping in noise models (Erbe et al., 2012; Williams et al., 2014b, 2015; Veirs et al., 2016; Cominelli et al., 2018), comparatively few have accounted for the small, private vessels that make up the majority of the coastal fleet in urban seas. Practical methods to track number, distance, and speed of boats that do not transmit AIS would improve the accuracy of sound field maps and noise impact assessments.

Theodolite tracking is a commonly applied land-based method used to measure fine-scale space-use and response to anthropogenic impacts, particularly the effect of maritime traffic on coastal marine mammals (Lusseau et al., 2009; Williams et al., 2009, 2014b; Christiansen et al., 2013; Piwetz et al., 2018; Sullivan and Torres, 2018; Currie et al., 2021). Photogrammetric methods to track small vessels around whales offer another approach to advance our knowledge on the acoustic contribution of small vessels. Photogrammetry is a widely used method for estimating the size of objects relative to reference points, including studies on the body condition of large marine vertebrates from satellite and drone imagery (Miller et al., 2012; Postma et al., 2013; Durban et al., 2016). Similarly, the geographic location of a target can be extracted from a photo given identification of fiducial points of known coordinates (Denardo et al., 2001; Awange and Kyalo Kiema, 2013). This method has been used to track vessel movements and compliance in high-traffic areas (Cope et al., 2020; Magnier and Gervaise, 2020), and can help account for small vessels that are typically left out of spatial and sound models.

The aim of this methodological approach is to explore whether it is possible to use photogrammetry to track boats without AIS, and compare our photogrammetry-derived positions and speeds with those derived from AIS and theodolite. Results from this study provide another land-based method for tracking boats that do not transmit AIS via a setup which is more cost effective than theodolite tracking at the data collection stage and can rely on a reduced field team. In fact, one motivation for this photogrammetric study was to collect data with fewer observers during a temporary restriction on the size of gatherings (and consequently, field crews) in Washington state during the early phase of the COVID-19 pandemic. This method allows for a new data stream to improve sound models by accounting for the impact of recreational vessels on the acoustic environment of coastal habitats important for species such as SRKWs.

2. Materials and methods

2.1. Study area

Equipment setup and in-field programming began in May 2020. Data were collected between 26 June and 25 September 2020 from three land-based observation sites on the west side of San Juan Island, WA (Fig. 1). The San Juan Islands are located in the traditional summer core critical habitat of SRKWs. The west side of San Juan Island borders Haro Strait which encompasses main shipping lanes to the Port of Vancouver in the north and includes popular recreational fishing spots. From north to south (1) San Juan County Park (CP) (48.5415038°, −123.1613389°) has an elevation of 14.4 m above sea level. (2) Hannah Heights (HH) (48.4948198°, −123.1188296°) has an elevation of 44.3 m above sea level and is ~200 m inland from the shoreline. (3) American Camp (AC) (48.4569559°, −122.9897422°) has a height of 70.4 m offering a view of the junction of the Strait of Juan de Fuca and Haro Strait.

A Sokkia DT540 digital theodolite with a precision of 5 s was connected to a laptop to collect all theodolite data. A custom computer software package (THEOPROG: written in Pascal and available from D. E. Bain) allowed us to obtain horizontal and vertical angles of whales and vessels (Kruse, 1991; Williams et al., 2002, 2009). The theodolite position was fixed to known locations at each site. A number of shoreline positions were collected using the theodolite at each site to verify accuracy, and tide height and curvature of the earth were accounted for. Tracking of both whales and vessels began 26 June 2020, and was used in conjunction with scan sampling efforts to capture killer whale behaviour and vessel activity in our field of view.

Photogrammetry data were collected using the Canon EOS R mirrorless body affixed to a Manfrotto tripod with an image dimension of 6270 × 4480 pixels. An intervalometer was used to capture three consecutive images every two minutes. The camera's position and frames across the field of view were fixed at each site (Figs. S1–S5). CP equipment was set up 5 m from the theodolite at an elevation of 15.2 m and field of view was captured in two frames at a focal length of 24 mm. HH equipment was set up 4 m from the theodolite at an elevation of 43.3 m and field of view was captured in three frames at a focal length of 35 mm. AC equipment was set up 6 m from the theodolite at an elevation of 70.5 m and field of view was captured in two frames at a focal length of 17 mm.

2.2. Tracking vessels

The tracking team consisted of one computer operator, one theodolite operator, and two scan samplers, one for whales and one for vessels. The computer operator recorded boat type, notable features and behaviours, and boat positions fixed on by the theodolite operator. The vessel scan sampler recorded boats within 1 km of the focal whale in 5-min increments (Altmann, 1974), and also operated the photogrammetry equipment. The camera was moved when the focal whale moved out of frame. All members of the team assisted in announcing focal whales and vessels transiting the field of view. The team collected vessel data using a combination of theodolite tracking and photogrammetry at all three sites starting on 15 July 2020.

2.3. Data processing

2.3.1. Theodolite

To achieve positions expressed in geographic coordinates, horizontal and vertical angles were converted to decimal degrees of latitude and

longitude using THEOPROG's Parse and Reform modules.

2.3.2. Photogrammetry

The custom C++ program 'Theo' was used to determine locations of targets within images (Figs. 2, S1; Veirs, 2020). Prior to processing, the camera's location was estimated to an accuracy of <1 ft. at each field site using real-time kinematic (RTK) positioning equipment in combination with existing data from San Juan Island surveyors, and changes in sea level were accounted for using tide charts. Knowing the height of the camera above sea level and accurate geographic coordinates of reference points (three in the background of the photo, one in the foreground; hereafter referred to as 'fiducials') provides the geometric framework for triangulating a target's location in the frame. Clicking on fiducials in each photo prompts the program to estimate relative positions of a selected vessel in UTMs (Universal Transverse Mercator). Unlike the theodolite system, the photogrammetry system 'Theo' did not account for the curvature of the earth so photogrammetry-derived range estimates were adjusted in the post-processing stage with a correction formula. The equation was derived from fitting a polynomial to the ratio of range under curved-earth to the range under flat-earth for angles taken at 1 min intervals between 90 and 60 degrees. The coordinates for each known vessel were converted to decimal degrees for mapping in QGIS 3.10 (QGIS Development Team, 2020), and timestamps were used to estimate speeds between points. Drift in the camera's clock was accounted for and adjusted to local NIST (National Institute of Standards and Technology) time. During preliminary review of the raw data, some vessels were moving at implausible speeds of hundreds of meters per second. To reduce some of this noise in the photogrammetry data, the latitudes and longitudes of processed vessels were averaged for each set of 3 consecutive photos taken over 5–6 s and reduced to a single position. These averaged positions were used to measure track length in QGIS and estimate photogrammetry-derived speeds in combination with the middle timestamp.

2.3.3. AIS

AIS data were obtained from SMRU Consulting's Lime Kiln database (SMRU Consulting, 2020). SQL queries were performed and separated for dates where data collection occurred during the field season. Dates were further broken down by session time to compare tracks to theodolite and photogrammetry. A 15 km boundary from the observers was used to filter vessels at great distances as previously determined under the Slowdown trial acoustic monitoring zone (Wood et al., 2018). AIS speed over ground and positions were used as "truth" to compare the methods and accuracy of theodolite- and photogrammetry-derived positions and speeds.

Vessel locations estimated from theodolite and photogrammetry were compared with AIS data in order to investigate error (Fig. 3). Distances were estimated between AIS, theodolite, and photogrammetry points recorded within 10 s of each other using QGIS. We estimated offsets and average speeds of known vessels to investigate the accuracy and precision of photogrammetry methods to measure speeds of boats around SRKWs. Estimated vessel locations and speeds from theodolite and photogrammetry were compared between both systems to determine differences in distances and speeds.

2.4. Statistical analyses

Distance and speed (calculated by time and distance between successive points) of vessels estimated using photogrammetry and theodolite were compared against AIS. For the purpose of this analysis, speeds and positions derived from AIS were taken as "truth" in order to facilitate comparison with theodolite tracking and photogrammetry. Speed was derived from the available time series of each vessel. Vessels off American Camp were generally too far away from the observation site to process accurately in photogrammetry (>6 km and concentrated at the edges of photogrammetry frames), making it nearly impossible to distinguish between vessels. As a result, our ground truthing used data from Hannah Heights and County Park in statistical analyses. We used

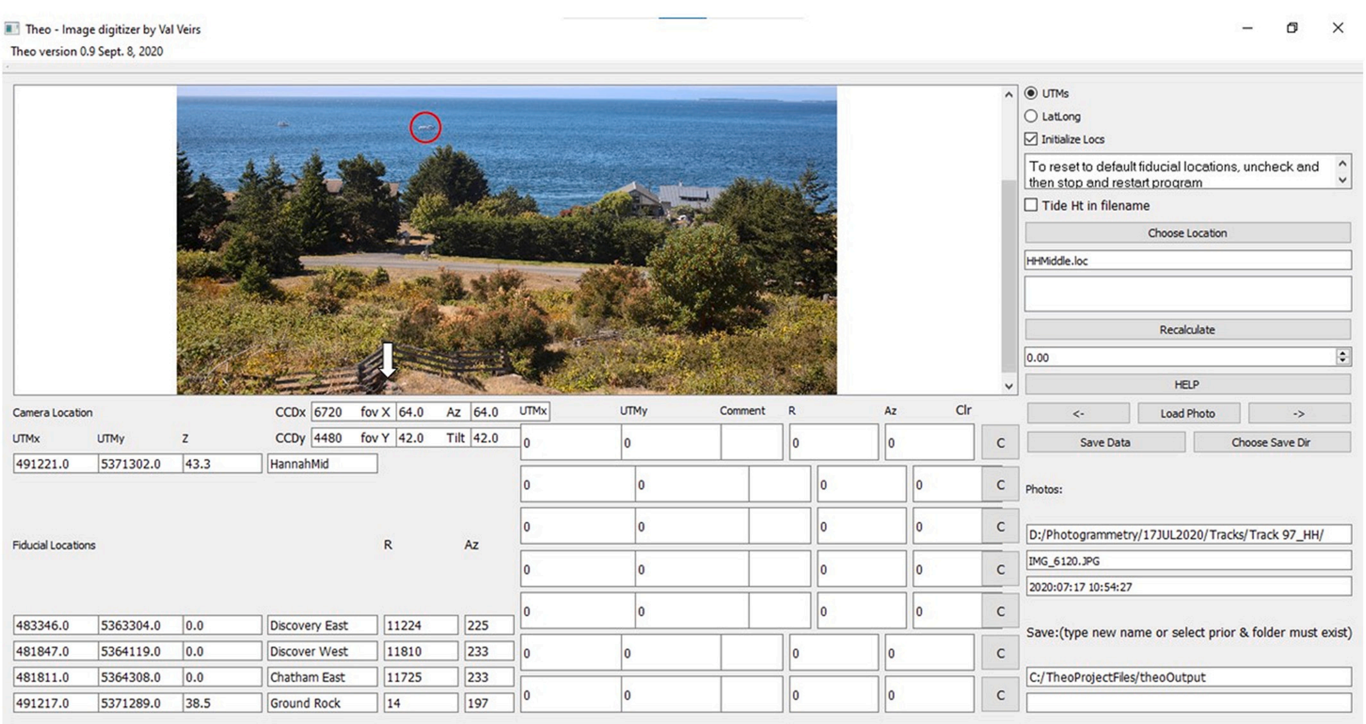

Fig. 2. Theo Qt C++ custom photogrammetry user interface to calculate vessel locations in Universal Transverse Mercator (UTM) coordinate system based on the known positions of fiducials in images (Orcasound, 2020). An example of a vessel processed using this custom software is circled in red and the foreground fiducial is marked with a white arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

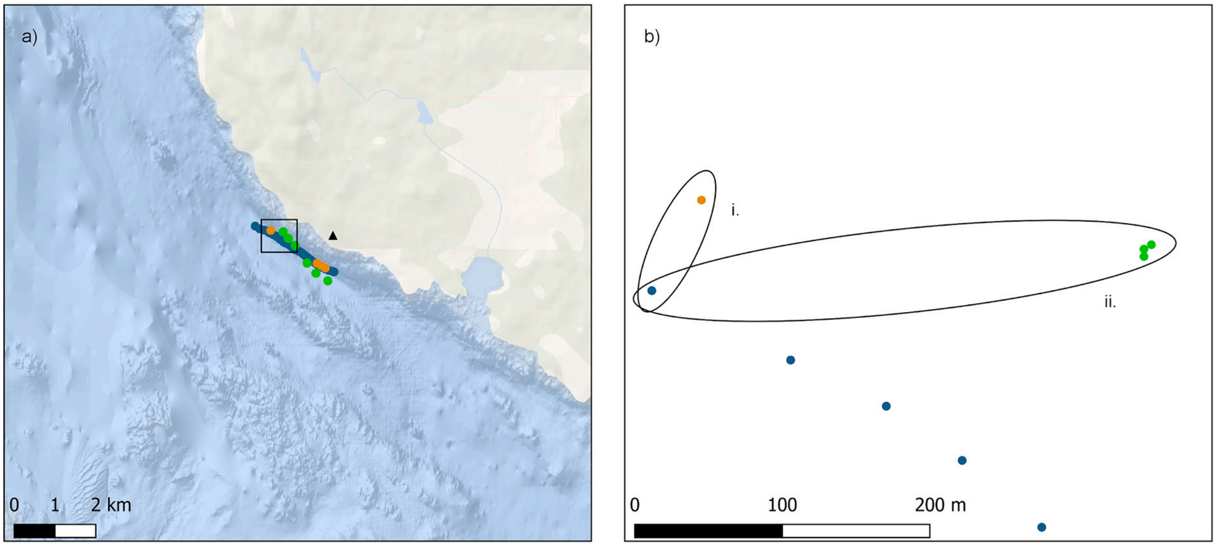

Fig. 3. Example of methods comparing positions between data types: (a) tracks of the same vessel using all experimental methods (AIS in blue, theodolite in orange, and photogrammetry in green) and (b) comparison of points recorded at the same time. Camera location is represented by a black triangle shown in (a). Distances are estimated between AIS, theodolite, and photogrammetry points recorded within 10 s of each other. (i) The theodolite and time-matched AIS points, 2 s difference, are approximately 70 m apart at 1562 m from the observers' position on land, treating AIS data as "truth". This represents an error of approximately 4.5% at a range of ~1.6 km. The estimated range from the observers' position on land to the theodolite point is approximately 1531 m. The difference in range represents an error of −2.0% at a range of ~1.5 km. (ii) The photogrammetry and time-matched AIS points, 8 s difference, are approximately 400 m apart at 1224 m from the observers' position on land, treating AIS data as "truth." This represents an error of approximately 3.3% at a range of ~1.2 km. The estimated range from the observers' position on land to the photogrammetry point is approximately 1223 m. The difference in range represents an error of −0.08% at a range of ~1.2 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

log-linear regression models to assess estimates of distance and speed over range from the observer and compare goodness of fit. The slopes of the regression lines and their 95% confidence intervals were assessed to determine bias, and adjusted R^2 values and coefficients of variation were calculated to measure accuracy. Error in photogrammetry speed was estimated across all ranges. All statistical analyses were performed using RStudio v.4.0.2 (R Core Team, 2020).

3. Results

Tracked vessels included private, commercial, and shipping, although the majority were Class B small, recreational boats and commercial whale watch vessels. On average, 68% of observed vessels in our study area did not transmit AIS. Range estimates derived from theodolite and photogrammetry were compared against AIS. A linear relationship

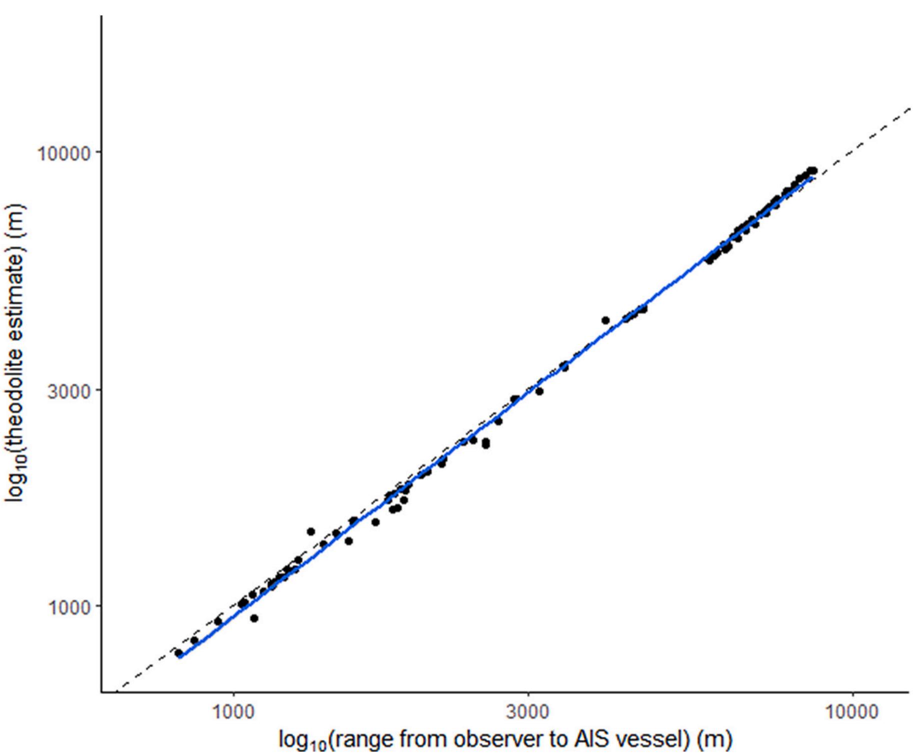

Fig. 4. Scatterplot showing the relationship between the ranges of unique AIS-equipped vessels (n = 16) from the observer (taken as truth) and ranges estimated from theodolite fixes (n = 85). The x and y axes are on a log scale. The dashed line from distance 0 m has a slope of 1. The solid blue line fits a smoothed linear regression with a slope of 1.03. 95% confidence intervals (1.02–1.04) are shaded in grey. Although there is some bias (~3%) in theodolite-derived range estimates, narrow confidence intervals show low variance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was observed when plotting log(theodolite estimate) against log(range from observer to AIS) (adjusted R^2 0.998; MSE 0.001) (Fig. 4). Confidence intervals showed some bias in theodolite-derived range estimates, although variance was considerably small. Similarly, a linear relationship was observed when plotting log(photogrammetry estimate) against log(range from observer to AIS) given a flat-earth model (adjusted R^2 0.906; MSE 0.051) (Fig. 5a). When range estimates were corrected for curvature, a linear relationship remained, but showed a lower fit (adjusted R^2 0.859; MSE 0.085) and introduced more bias (Fig. 5b). While both theodolite- and photogrammetry-derived ranges provided a suitable fit, a higher R^2 value showed that theodolite estimates were more precise than photogrammetry-derived estimates.

A comparison of speed estimates, derived from distance and time between vessel positions, showed linear, unbiased relationships between both theodolite and AIS (adjusted R^2 0.8233; MSE 0.088) (Fig. 6), and photogrammetry and AIS (adjusted R^2 0.553; MSE 0.303) (Fig. 7). Speeds from photogrammetry data had higher variance than those from theodolite and did not show a clear pattern of under- or overestimation. At a range of ~7.5 km from the observer, photogrammetry-derived speeds were overestimated by a factor of 2 (Fig. 8).

4. Discussion

This study demonstrated the use of two methods to estimate distance and speed of vessels without AIS in a highly trafficked coastal environment. The best estimates of both distance and speed were derived from theodolite data, although there are benefits and limitations inherent in both methods (Table 1). Placing the photogrammetry camera at the same field sites as the theodolite reduced our ability to accurately distinguish vessels in and across successive images. The extra elevation and distance from shore required to collect more accurate theodolite data (Piwetz et al., 2018) resulted in images that often had clusters of vessels, particularly small, generic private boats, concentrated at the edges of frames. While this method would be more optimal at a study site closer to shore, the photogrammetric approach has certain benefits to building more inclusive soundscape models for management that theodolite and AIS alone cannot provide.

Linear relationships were observed for both methods in estimating distance, although the model comparing theodolite against AIS-derived positions was unbiased and provided a more suitable fit than photogrammetry. Correcting for curvature did not improve the fit for photogrammetry-derived range estimates (evidenced by a slightly lower adjusted R^2 and slope farther away from 1), suggesting that the curved-earth model overcorrects to the point that introduced bias is greater than the error of the flat-earth model. The correction increases with distance; when range is large, and the uncertainty in range is substantial, there is large uncertainty in what the correction factor should be. Since THEOPROG provides a better fit for theodolite data when correcting for curvature, it may be the case that this overcorrection results from noise inherent in photogrammetry data. If that is the case, efforts can be made to reduce noise in future studies, which would minimize introduced bias. On average, ranges derived from photogrammetry were slightly overestimated and increased with increasing distance from the observer, particularly at ranges >3 km. When compared to AIS, speeds derived from both theodolite and photogrammetry positions showed a linear, unbiased relationship. Despite unbiased relationships, both experimental methods had reduced accuracy when estimating speed in comparison to estimating distance. Both the camera used in this study and the theodolite have a nominal precision of 5 s, which equates to 720 steps per degree. Calibrating the theodolite prior to data collection suggested that precision may actually have been closer to 20 s, or 180 steps per degree. As technology improves, upgrading to a camera with even an increased pixel density of 7200 vertical pixels (as opposed to 4480 pixels in this study) could reduce variance and result in accuracy comparable with the theodolite. Both methods require finding a balance between bias and variance, however logistical constraints may inform decisions in research design. In previous SRKW theodolite tracking studies, an effort was made to use two theodolite crews (6 people) to track SRKWs and boats separately (Williams et al., 2009). In response to the COVID-19 pandemic, Washington state issued a ban on large gatherings outside of socially isolated households. Replacing observers with a camera allowed four observers to do the work of six, but the tradeoff was a vastly increased workload at the data processing and analysis stage.

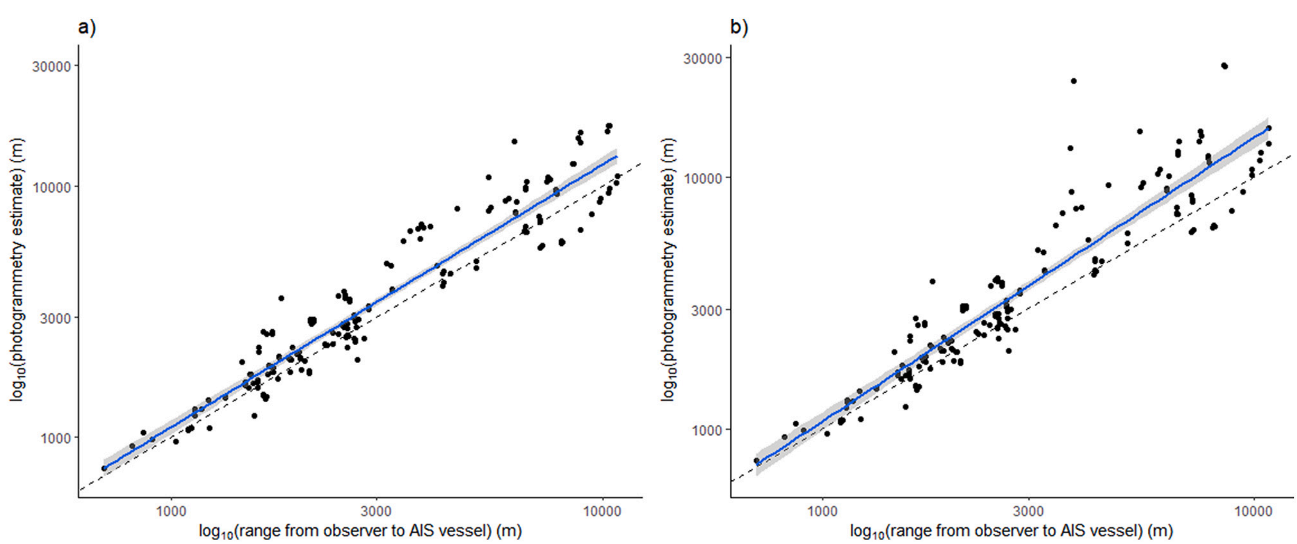

Fig. 5. (a) Scatterplot showing the relationship between the ranges of unique AIS equipped vessels (n = 20) from the observer (taken as truth) and ranges estimated from uncorrected, flat-earth PG positions (n = 178). The x and y axes are on a log scale. The dashed line from distance 0 m has a slope of 1. The solid blue line fits a smoothed linear regression with a slope of 1.05. 95% confidence intervals (1.00–1.10) are shaded in grey. (b) Scatterplot showing the relationship between the ranges of unique AIS equipped vessels (n = 20) from the observer (taken as truth) and ranges estimated from PG positions corrected for curvature of the earth (n = 171). The x and y axes are on a log scale. The dashed line from distance 0 m has a slope of 1. The solid blue line fits a smoothed linear regression with a slope of 1.13. 95% confidence intervals (1.06–1.20) are shaded in grey. Confidence intervals for both photogrammetry-derived range estimates show relatively low variance, although there is some bias, particularly at the greatest distances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

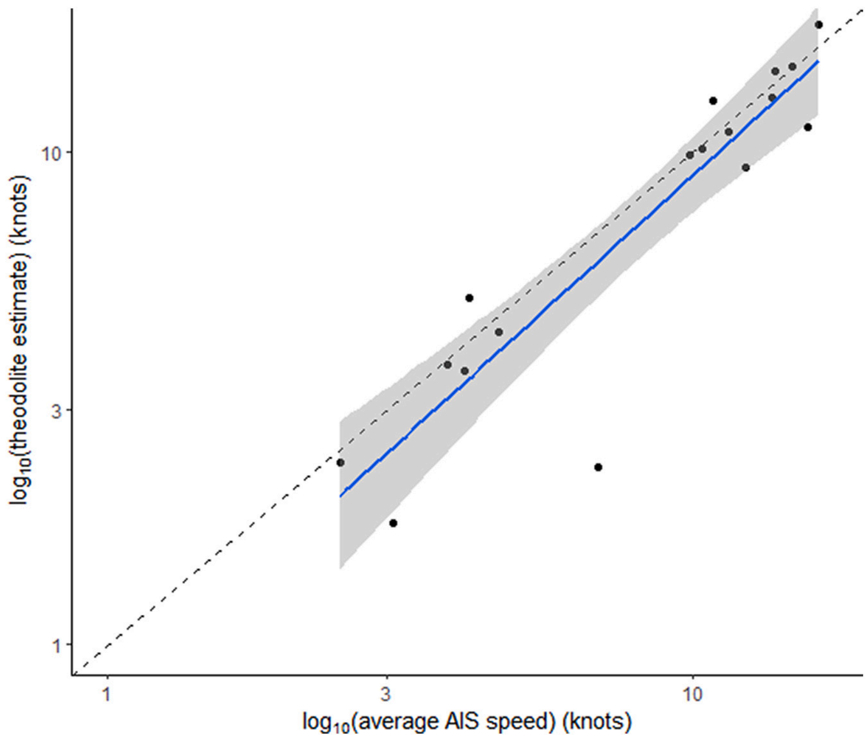

Fig. 6. Scatterplot showing the relationship between the speeds of unique AIS-equipped vessels (taken as truth) (n = 9) and speeds estimated from theodolite fixes (n = 17). The x and y axes are on a log scale. Speed from AIS and theodolite tracks were estimated over comparable 10 min periods. The dashed line from speed 0 knots has a slope of 1. The solid blue line fits a smoothed linear regression with a slope of 1.08. 95% confidence intervals (0.82–1.34) are shaded in grey and show an unbiased relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

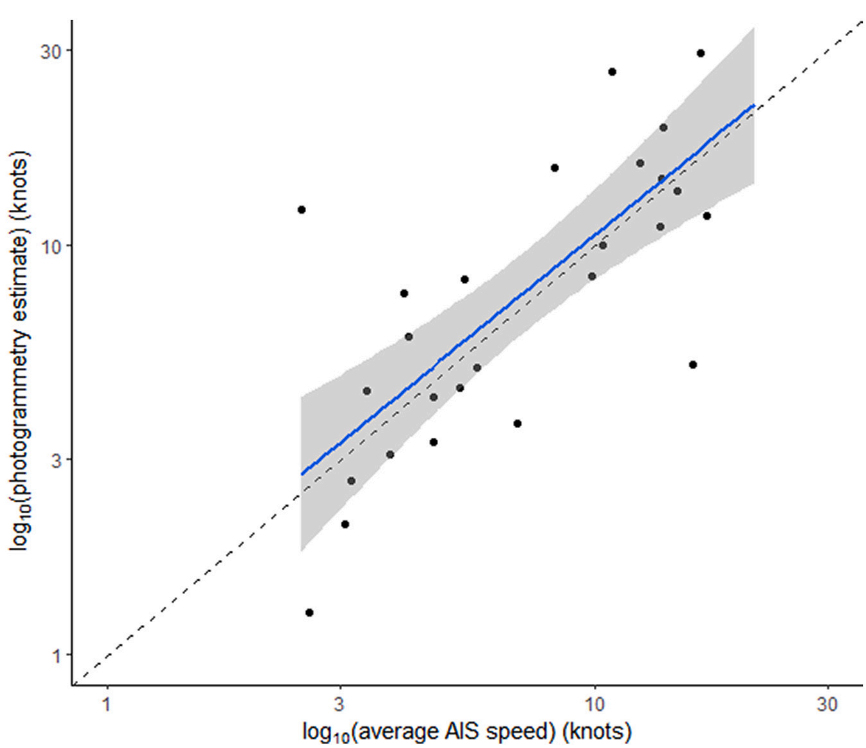

Fig. 7. Scatterplot showing the relationship between the speeds of unique AIS equipped vessels (taken as truth) (n = 13) and speeds estimated from PG positions (n = 27). The x and y axes are on a log scale. Speed from PG positions were estimated over the total time the vessel was in frame. The dashed line from speed 0 knots has a slope of 1. The solid blue line fits a smoothed linear regression with a slope of 0.97. 95% confidence intervals (0.62–1.32) are shaded in grey and show an unbiased relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Results from this study are reflective of this particular coastal environment and study area. While AIS was taken as “truth” for its reliable system, error in AIS measurements should be kept in mind (Bailey, 2005; Harati-Mokhtari et al., 2007). Although photogrammetry provided suitable distance estimates, there was some variability in the data. Noise generated by small boats varies widely depending on their speed (Wladichuk et al., 2019). Therefore, accurate data on vessel speed are particularly important for predicting noise exposure and understanding the behavioural responses of marine mammals. It is important to note there are some sources of error inherent with the study design, particularly related to program limitations (e.g., not accounting for the curvature of the earth) and manually processing images. The height and distance of observation sites, a requirement for theodolite studies, and depth of field made vessels at the edges of view difficult to identify in images. If small vessels were out of focus it was increasingly difficult to recognize them in sequential photos. Given the distance between the

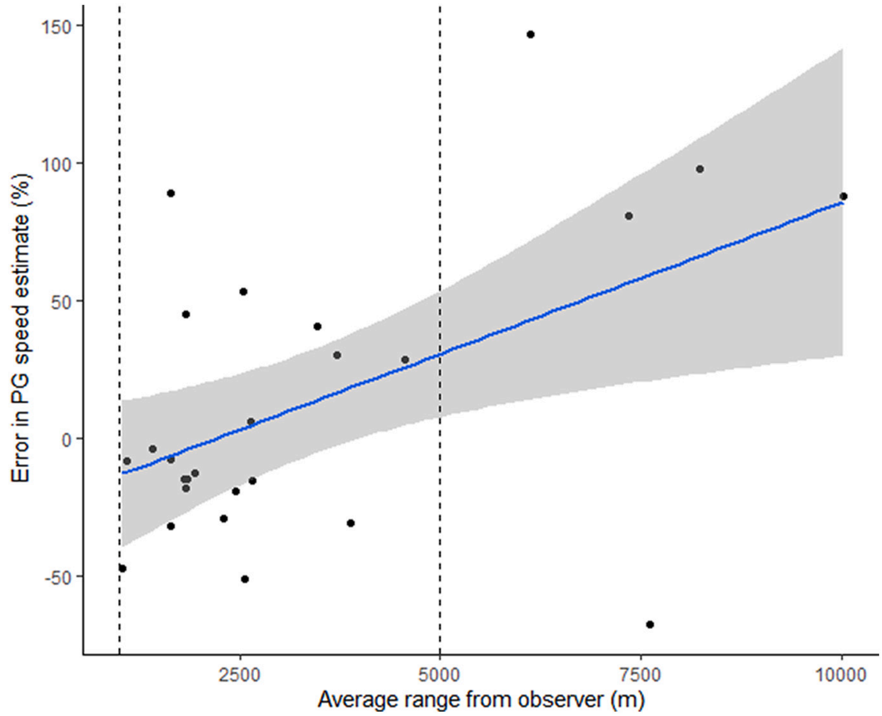

Fig. 8. Scatterplot showing the relationship between percent error in photogrammetry speed estimates (n = 27) and increasing range from observer (reported as an average over three consecutive images taken in a 5–6 s period). The vertical dashed lines are highlighting predicted error at ranges between 1000 m (−13.25%) and 5000 m (30.69%).

Table 1
Benefits and limitations of each methodological approach in obtaining vessel data.

Methodological approach	Benefits	Limitations
Photogrammetry	1. A more cost-effective method (equipment and personnel) 2. Only requires a reduced field team of one or two members to collect data 3. This captures and digitizes the activity of noncommercial vessels or those without AIS in view immediately 4. Open-source software	1. Better suited to locations closer to shore 2. Long post-processing time 3. Requires large storage space for high quality image files 4. Software setup for post-processing can be challenging[a]
Theodolite	1. Traditional method widely used for tracking animal and vessel movement 2. Fast post-processing time 3. Existing, free software shows some results in real time to facilitate troubleshooting	1. Expensive equipment 2. Requires at least two people to collect data 3. Limited data capabilities (i.e. an explicit tradeoff between tracking whales and vessels with only one theodolite team)
AIS	1. Easy to access 2. Fast post-processing time	1. Limited to AIS-transmitting vessels 2. Costly to download from an external source 3. Consumer equipment and setup are typically not user friendly 4. Missing or incomplete messages are possible

[a] Contact vveirs@coloradocollege.edu for questions (Orcasound, 2020).

camera and water, and because small recreational boats were often clustered in the corners of photogrammetry frames, there was a paucity of data at ranges <1 km from the observer, a distance relevant to management. Our data were further limited by photo quality which varied with environmental conditions. Averaging positions to reduce error may have underestimated distance travelled along a track due to its failure to capture all course changes. However, this method could overestimate distance by adding the remaining photogrammetry noise to the track length. Statistically, these two biases roughly canceled out, resulting in an unbiased estimate of speed. Potential improvements to our study's photogrammetry design can be inferred from previous research using shore-based photographic monitoring systems in high-use vessel traffic environments. For example, visual monitoring with GoPro cameras was used to estimate positions of boats through an image processing system (Magnier and Gervaise, 2020). Similarly, small vessels were detected using a camera fixed-position and processed with the autonomous Detector of Small Marine Vessels (DSMV) in southern Vancouver Island, BC (Marques et al., 2021). Although automated processing could reduce error and would significantly decrease processing time, the methods used in our study could be improved by setting range limits. Related studies using manual detection of boats through photographic monitoring systems have also been proposed. In San Francisco Bay, positions and speeds of vessels with and without AIS were derived from the autonomous Marine Monitor (M2) system and photographs captured with a marine-radar sensor (Cope et al., 2020). This radar was used to track vessels within a 9 km range, but would not necessarily improve our study. Further research would be required to assess the applicability of other methods.

Efforts to understand the role of vessel impacts on SRKW population decline are especially driven in the Salish Sea. Models of SRKW behaviour showed increased foraging during the voluntary Port of Vancouver ship slowdown between July and October 2019 as a result of a reduction in vessel noise (Williams et al., 2021). Given that noise effects from smaller vessels are disruptive (Houghton et al., 2015), speed and distance of all vessels in SRKW habitat should be considered in mitigation measures. Washington's new commercial licensing program went into effect in the summer of 2021, limiting both the number of whale watch vessels around SRKWs from July–September, as well as the amount of

time each operator can spend viewing them within 0.5 nmi (S.B. 5577). If these management measures successfully cap commercial vessel activity to a maximum of 3 boats within 1000 m of the whales, this could represent an opportunity that we have rarely observed in decades (e.g., vessel traffic levels were higher than this even as recently as 2003–05 (Williams et al., 2009)), with the caveat being that such regulations would not apply to non-commercial vessels. Monitoring the effectiveness of these new regulations in US waters could inform Canadian management actions that are evolving quickly to protect endangered whales and dolphins (Williams et al., 2014c, 2020).

Emerging methods are attempting to quantify the relative importance of noise and disturbance from ships and boats in disrupting SRKW foraging behaviour (Williams et al., 2021). Accurate data on number, distance, and speed of boats is needed to inform such modeling efforts, but data collection on boats cannot come at the cost of accuracy and precision of data collection on SRKW behaviour (Table 1). Our photogrammetry design uses a cost-effective and land-based monitoring system to measure position and speed of vessels without AIS. It's advantage of allowing a reduced field team given personnel restrictions also ensured that all vessels in view could be tracked without sacrificing data related to SRKW behaviour. While other factors including directionality of emitted noise, variation among individual vessels, and sound propagation conditions are important, they were beyond the scope of this study. Here we have shown more than two-thirds of the vessels transiting these waters do not use AIS, suggesting AIS-derived sound models underestimate vessel noise. This approach has allowed us to assess effort, accuracy, and precision in estimating vessel speed with three different methods. AIS requires minimal investment given that the data are readily available, but in coastal waters such as Haro Strait, this system did not account for the majority of vessels (68% in this study). Photogrammetry is a step-up in effort, requiring a high-quality camera with an appropriate setup, and post-processing can be extremely time intensive if an automated system is not in place. Although theodolites are also expensive and must be operated by a dedicated observer to collect consistent data, the resulting positions allow for reliable estimates of vessel behaviour, including speed. Given the tradeoff in bias and variance across methods, researchers should choose which method is most appropriate for their objectives, particularly whether absolute or relative positions are needed. If the goal is to reconstruct sound fields around whales, it is the relative positions that are important, so some error in absolute position is tolerable. With improvements, the methods used in this study could support management involved with collision and noise risk assessments for the critically endangered SRKW population and other species vulnerable to anthropogenic impacts. Future work should focus on placement of the camera (e.g. closer to shore) and camera quality. Given rapid changes in vessel management from year to year and the status of the SRKW population (Lacy et al., 2017), continued long-term monitoring is critical to determine effective strategies for mitigating threats to their survival and recovery, adapting management, and complementing ongoing research programs.

CRediT authorship contribution statement

EA, LTB, MSC, and RW conceived of the study; CFL, KAN, AMB, and SAR performed data collection, CFL, KAN, DEB and RW completed the analysis; and CFL, KAN, AMB, SAR, DEB, and RW contributed to the writing of the manuscript.

CRediT authorship contribution statement

Catherine F. Lo: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kimberly A. Nielsen:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Erin Ashe:** Conceptualization, Funding acquisition, Project administration, Methodology, Resources, Supervision. **David E. Bain:** Data curation, Formal analysis, Methodology, Software, Validation, Supervision, Writing – review & editing. **Andrea Mendez-Bye:** Data curation, Investigation, Methodology, Software, Validation. **Stephanie A. Reiss:** Data curation, Investigation, Methodology, Software, Validation, Writing – review & editing. **Laura T. Bogaard:** Conceptualization, Methodology. **Marena Salerno Collins:** Conceptualization, Methodology. **Rob Williams:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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