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Theodolite Tracking in Marine Mammal Research: From Roger Payne to the Present

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Abstract

In the early 1970s, Roger Payne and colleagues developed a non-invasive, shore-based method for collecting data on free-ranging marine mammals in their natural environments. By using a theodolite, or surveyor's transit, they were able to collect data on nearshore marine mammal movement patterns, habitat use, and behavior without any disruption to the animals. As technology advanced, theodolite data collection progressed from analog machines requiring manual data entry to digital equipment linked to computer software that facilitated data management and automated calculations of marine mammal positional information. There are limitations associated with theodolite use, and concurrent data collection methods can contribute information that may not be possible with shore-based research alone. Since the first published research in 1978 using a theodolite to describe the behavioral ecology of dolphins off Argentina, at least 46 species of marine mammals in 36 countries have been tracked by theodolite, and the method continues to be used globally to contribute to non-invasive marine mammal research, conservation, and management.

Key Words: theodolite, marine mammal tracking, movement patterns, land-based

Introduction

Understanding animal behavior is important for answering a broad range of biological and evolutionary questions, and to inform conservation management, yet systematic studies of live marine mammals in their natural environment only began to emerge in the late 1960s. Prior to this time, information was primarily derived from harvested, stranded, or captive marine mammals (Andersen, 1984). Early descriptions by Caldwell (1955) and Schevill & Backus (1960) paved the way for studying marine mammal behavior in natural settings by showing that data could be obtained on individual free-ranging cetaceans at sea (for reviews on the history of marine mammal research, see Samuels & Tyack, 2000; Würsig et al., 2018). Roger Payne played a large role in this paradigm shift by presenting some of the first studies based on focal observations of free-ranging marine mammals, primarily mysticetes, which did not involve deceased or captive animals (Andersen, 1984). Payne's (1983) volume *Communication and Behavior of Whales* includes 14 works by 26 authors that represent early long-term scientific studies of marine mammal behavior as studied in the natural environment.

The observation of marine mammal behavior in aquatic environments presents a number of challenges. Marine mammals can be elusive as they remain under water for extended periods, surface for only seconds at a time, move quickly, and range large distances. Several technologies have been borrowed and adapted from established terrestrial animal research, and new technologies have been developed to observe animals in challenging marine conditions (see several techniques reviewed in Whitehead et al., 2000).

Platforms of observation vary, including land, sea, subsea, and air. Each have advantages and disadvantages based on research goals, species of interest, and the available budget. Many research methods introduce a degree of potential disturbance to marine mammals that can alter "natural" behaviors at one or more stages during the course of research. There are several exceptions, including observational studies from land, passive acoustic monitoring (PAM), scat or sloughed skin collection (depending on proximity to and behavior around study subjects), and potentially drones (depending on distance from study subjects). These benign approaches are especially attractive in behavioral work because they do not alter animal behavior as, for example, close boat approaches may (Kruse, 1991).

Land survey theodolites (surveyor's transits) have been adapted to study marine mammals (e.g., cetaceans, sirenians, pinnipeds, sea otters, and polar bears) at sea and in a non-invasive manner. Operated from land or ice, the theodolite enables collection of precise locations of nearby marine mammals at the surface of the water. It is a powerful tool for documenting surface movements within relatively small spatial scales and to collect data on sources of potential disturbance in the vicinity, such as maritime vessels, simultaneous to animal and group position, behavior, and movement data. The resourceful idea to adapt surveying techniques to study marine mammals from shore was first introduced by Roger Payne in 1972, and the theodolite quickly became the preferred method for recording precise geographic positions of cetaceans that occurred near the coast (Samuels & Tyack, 2000). Herein, we give a brief description of the modern digital theodolite, a history of its application in marine mammal research, software systems developed to facilitate theodolite data collection, and analytical considerations. We also present the results of a literature review and Web-based survey relating to theodolite use in marine mammal research.

Theodolite Description

A transit theodolite is a precision instrument designed for engineering applications that measures gravity-referenced vertical angles relative to the zenith (i.e., the position directly above the theodolite) and horizontal angles relative to a stable object of known location and bearing from the theodolite. Modern theodolites have a high degree of accuracy, within 1 to 5 s of arc. In an engineering context, targeting a stationary object at 100 m using an instrument with 5 s precision is equivalent to placing the theodolite crosshairs within 2.5 mm of the desired target position (Stibor, 2013). Precision is reduced when the target is at greater distance or is moving, environmental factors interfere (e.g., fog or heat haze), or if human error occurs. Theodolites have a monocular eyepiece with a fixed magnification, typically 30x, which gives the operator an enhanced view of distant objects. The monocular has a central crosshair with reticles and swivels along the vertical axis, while the base of the theodolite swivels along the horizontal axis to precisely "target" an object. In marine mammal research, when looking through the eyepiece, the crosshair is positioned on an object (e.g., animal or vessel) at the water line to obtain vertical and horizontal angles. With known station parameters, including geographic position and elevation above mean low sea level, tide height to correct for that elevation minute by minute, and the horizontal reference azimuth, angles can be used to calculate the geographic location of objects on the water using distance approximation equations (Lerczak & Hobbs, 1998). Once multiple positions are obtained, movement parameters (e.g., speed of movement, heading, bearing change, and linearity of movement) and distances between objects (e.g., between individual animals, animal and vessel/sound source, and/or animal and PAM device) can be calculated. During analyses, marine mammal positions can also be overlaid on other geographical layers, such as bathymetric features or salinity gradients, to better understand habitat use of the near-shore area. Given ever-increasing human-related activity along coastal regions, such information is critical for making informed marine mammal management decisions.

Theodolite Use in Marine Mammal Research

While Roger Payne had the idea of using a theodolite for tracking marine mammals, the first published accounts appeared in Würsig (1978) and in Würsig & Würsig (1979, 1980); these works described common bottlenose dolphin (*Tursiops truncatus*) and dusky dolphin (*Lagenorhynchus obscurus*) behavioral ecology off Argentina. Braham et al. (1978) produced a preliminary report for the National Marine Fisheries Service (NMFS) using theodolite tracking techniques to study bowhead whale (*Balaena mysticetus*) migration onset and termination near Barrow, Alaska, with a full account in Rugh & Cubbage (1980). Clark & Clark (1980) described southern right whale (*Eubalaena australis*) responses to sound playback experiments using theodolite tracking, photo-identification, and acoustic methods. Tyack (1981) described interactions between singing humpback whales (*Megaptera novaeangliae*) in Hawaii using theodolite and boat-based methods concurrently. These initial studies provided the foundation for theodolite use in marine mammal research, showing that accurate locations of odontocetes and mysticetes could be obtained to investigate a variety of questions related to behavior, movement patterns, and responses to human activity without additional disturbance. Nearly 50 years later, the theodolite continues to be used worldwide to study marine mammal behavior and movement patterns that contribute to our understanding of their natural history, conservation, and management.

In addition to published research that incorporates theodolite tracking as a means to study marine mammals, several papers have been published on techniques for using theodolites and for improving the accuracy of positional data. For example, Mayo & Goodson (1993) presented a practical guide at the European Cetacean Society conference describing the use of surveying instruments to collect positional data of cetaceans from land. Sagnol et al. (2014) presented a regression-based correction to improve the accuracy of position information collected along the vertical axis when tracking animals at increasing distances from shore. Theodolites have also been used in marine mammal research as a form of Quality Assurance and Control (QA/QC) to evaluate observer distance estimation reliability and consistency (Lusseau et al., 2009).

Computer-Based Programs

The first theodolites used in marine mammal tracking were analog and lacked the means to collect, calculate, and transfer data to external storage devices. At the time, data collection involved laborious efforts to record angles manually or by voice recorder and later transcription into a useable format for data analysis. Researchers were also tasked with calculating Cartesian (x-y) coordinates and/or geographic positions *post hoc* based on theodolite angle readings and station parameters. In 1976, Jan Wolitzky developed the first computer program to automate these calculations for positions of objects on a curved Earth (for a detailed description, see Würsig, 1978). Years later, Frank Cipriano (1990) developed *T-Trak* (a theodolite-tracking data analysis program) to analyze data collected on dusky dolphins off New Zealand. This program had the added benefit of digitally storing data from an electronic theodolite in real time and then sorting, recalculating, and exporting text files *post hoc* (Gailey, 2001).

As modern electronic theodolites were employed, data collection and direct digital transfer to recording devices (e.g., field computer) became possible, enabling researchers to collect more data in less time while eliminating the risk of transcription errors. Computer programs allowed researchers to record positional and other information on moving targets. For example, *Aardvark*, developed by Harold Mills in the 1990s, enables a direct theodolite–computer interface and was first used with humpback whales off Hawaii (Frankel & Clark, 1998). *Pythagoras*, developed in 2000 by Gailey & Ortega-Ortiz (2002), can record additional variables (e.g., behavioral data) and includes real-time calculations and trackline display. Also in 2000, *Cyclops Tracker*, now called *VADAR* (*Visual Detection and Ranging at sea*), offers real-time calculations and trackline display (Kniest et al., 2000). *Pythagoras* and *VADAR* were the first systems to incorporate emerging geographic information system (GIS) techniques (see Gailey & Ortega-Ortiz, 2002, for a full description and comparison of the five programs listed above). In 2016, HDR, Inc. began field testing *Cetacean Observation and Marine Protected Animal Survey Software* (*COMPASS*; Richlen et al., 2018) developed for U.S. Navy-funded projects involving diverse data collection platforms, including land-based theodolite tracking. *COMPASS* integrates mobile and Web technologies across multiple platforms (e.g., land, boat, and plane) and was designed to streamline and standardize data collection and management to meet U.S. Navy Marine Species Monitoring (MSM) standards. This software is not widely available to the public. The latest program to emerge for large-scale use is *Mysticetus*, developed by Entiat River Technologies (Steckler, 2011), which merges GIS, infra-red (IR) cameras, and cloud storage involving multiple sampling methods. These programs have made important contributions to the study of marine mammals by providing researchers with the capacity to collect and manage large datasets efficiently and to process and display results.

Analytical Considerations

Theodolite data can be used to determine an animal's swimming speed, distance traveled, linearity, direction of movement, distance from an object or shore, and the orientation of animals to each other. Although theodolites have been useful instruments to obtain marine mammal spatio-temporal data, they present a number of analytical challenges. Movement data are often defined and sampled by some unit of space or time to minimize issues with oversampling/undersampling (Turchin, 1998). For some marine mammals, such as large dolphin groups (wherein at least one individual is likely up at the surface at any given time), this can be done by recording a position at a defined period of time (e.g., every 60 s). However, for individuals or groups that dive out of sight, it is impossible to obtain equal space/time sampling points. For example, large whales can be tracked at the surface for a few minutes with 20 s blow intervals, but tracking ceases during extended periods when whales are submerged. Resampling regimes are typically employed based on evaluation of the spatio-temporal autocorrelation in the movement data to mediate uneven sampling points. Without this, data are biased toward the surface period since more points are obtained. For most marine mammals, behavior at the surface is different compared to dive behavior, which limits extrapolation and interpretation. Another challenge is that the tracking data usually vary in temporal duration, so the value for linearity of movement, for example, would be different if the observer tracked an animal for 10 min compared to 1 h. One approach is to bin movement data into defined periods (e.g., 10 min of observation), but this can lead to pseudo-replication (Hurlbert, 1984) of sampling units based on the individual, track, or behavioral state of the animal. Weighting the observation period to the track/individual has been used to minimize analytical pseudo-replication. However, individual pseudo-replication or individual movement heterogeneity is often unknown in theodolite studies since identification of the individual in a group is not normally possible.

Although movement patterns derived from theodolite data assume the animal has travelled in a straight line, other research methods for tracking marine mammal movement may also assume straight line movement. For example, positions of satellite-monitored marine mammals are effectively transmitted only when an animal surfaces and the transmitting antenna is exposed above sea water. Furthermore, satellite systems such as Argos are associated with errors that result in inaccurate positions from several meters to 1 km (Vincent et al., 2002). This type of tracking may be preferred for broad, long-range movements, but does not offer the fine-scale position information and concomitant visual observations that are possible with theodolite tracking. Accelerometer and magnetometer tags, such as DTAGS, can provide high-resolution information when the animal is submerged that is lacking with theodolite tracking, but they often require frequent position updates due to errors associated with changes in environmental features such as pressure and temperature (Johnson & Tyack, 2003).

Theodolite tracking of marine mammals provides information on habitat associations and anthropogenic interactions such as ecotourism, marine construction, pile driving, dredging, and seismic surveys. Animal movements can indicate an aversive response, although other factors can affect movement, including behavioral state, prey availability, sex, age, reproductive status, sensitization/habituation, and environment (e.g., sea state, tide, water temp, and water depth), and should be considered to ensure natural variation in behavior is not masking the effects of anthropogenic exposure. Given the number of potential variables that can influence animal movements, multivariate analyses are typically conducted to assess individual and/or population-level changes in behavior relative to natural and human-generated disturbances.

Theodolite tracking studies tend to have more statistical power to understand movement patterns than other tracking applications such as biotelemetry. Tagging studies often yield data on a few individuals due to the expense and logistical challenge of tagging marine mammals, whereas theodolite studies can acquire data on multiple individuals/groups at the same time and can obtain sample sizes in the hundreds. Power analyses on movement parameters of western gray whales (*Eschrichtius robustus*) have shown that at least ~50 tracks would be needed to detect a large change (50%) in the animal's movement pattern, while ~1,000 tracks would be required to detect more subtle (10%) changes in the animal's behavior (Gailey et al., 2016). Therefore, sample sizes are important, especially when exposure to an activity occurs over a relatively short time (months). Obtaining baseline, undisturbed data is also essential for understanding how animals behave relative to different environmental/anthropogenic exposures.

Tracking Data and Accuracy

A number of factors can affect the accuracy of marine mammal positional information collected using a theodolite, including observer experience, height of theodolite above sea level, and environmental conditions. Observer experience is an important factor as it takes substantial practice to track individuals/groups of marine mammals, particularly for animals that surface for only seconds to breathe. Such rapid determination of an animal's or group's location, and the ability to quickly maneuver theodolite crosshairs to the correct position, can introduce a considerable amount of error into the position estimation and movement variables derived from them. Study site selection is important and should be relatively close to the water, at a suitable height above sea level, with an unobstructed view, and in an area where animals move relatively close to shore (< 10 km from theodolite, depending on site elevation and study species). A general rule of thumb for station height is between 20 m (e.g., when tracking dolphins up to 5 km away; Würsig et al., 1991) and 45 m above mean low sea level. Tracking animals from very low or high elevations can introduce errors associated with the curvature of the Earth. Coastal cliffs, hills, or sand dunes with established flora can present a natural area with optimal elevation and distance to shore. Still, many seaside and river bank areas lack naturally elevated landscapes, thus requiring creative solutions when establishing a study site. Researchers use rooftops and balconies of hotels and airport buildings, lighthouses, historic fortifications, and grounded oil rigs (semi-submersible oil rigs tend to move with swell, even in calm conditions; Goodson & Sturtivant, 1996); and they have built independent elevated structures to increase observation height (Figure 1). Gailey et al. (2016) used specially designed wooden towers with independent stable central structures on which only theodolites were placed, where observers could move freely on the unattached towers without introducing errors (Figure 1). Since theodolites are gravity referenced, it is critical that they remain balanced and calibrated so that errors are not introduced into the position data.

In addition to having relatively high elevation near shore, an accurate station height must be known to within approximately ± 10 cm, which requires initial careful surveying of the site (Würsig et al., 1991). Total stations are digital theodolites with onboard computers that use data from additional instruments, such as laser range finders, to measure line-of-sight distance that can be used to calculate accurate station height. Considering a right-angled triangle, with a known line-of-sight distance to the waterline (i.e., hypotenuse; acquired by laser range finder) and acute angle (i.e., vertical angle; acquired by the theodolite eyepiece), the platform elevation above mean low sea level can be determined using basic trigonometry and tide height at the time of measurement. Alternative approaches for calculating station height using a standard theodolite without a laser range finder have been described to increase position data accuracy (Bailey & Lusseau, 2004; Frankel et al., 2009).

The accuracy of positional information is also affected by a number of environmental conditions. Theodolite tracking is possible during daylight hours without fog obstruction, when animals are visible, and when wind-driven waves are generally less than Beaufort sea state 5. Researchers may compensate for some of these limitations by incorporating alternative methods concurrently such as PAM and/or nighttime viewing using infrared scopes. Environmental conditions such as heat haze, sun glare, sea swell, and atmospheric refraction can affect the accuracy of positional information. Heat haze, created by a variation in temperature between the sea surface and air, produces a blurred, shimmering effect that is exaggerated when viewed through a magnified lens. Atmospheric refraction is the deviation of light waves due to air density variation and distorts images of distant objects, creating a mirage effect that stretches and compresses images. These blurring and distortion effects reduce the ability to focus the theodolite crosshairs accurately and precisely on the focal animal at the water surface. Non-theodolite studies using binoculars and video have integrated a correction for refraction error based on air temperature and barometric pressure collected *in situ*, which might be considered for data collected by theodolite (Gordon, 2001; Kinzey & Gerrodette, 2003).

Figure 1. Examples of diversity in theodolite station platforms: *Top left:* Bernd Würsig and Texas A&M University graduate students tracking common bottlenose dolphins (*Tursiops truncatus*) off Galveston, Texas, in the 1990s from a hotel rooftop (32 m). *Top right:* Olga Sychenko tracking western gray whales (*Eschrichtius robustus*) off Sakhalin Island, Russia, in 2010 from a specially constructed platform (8 m). *Bottom:* Mott MacDonald field team members tracking Indo-Pacific humpback dolphins (*Sousa chinensis*) off Hong Kong in 2015 from a naturally elevated landscape (51 m). Photos courtesy of Bernd Würsig, Glenn Gailey, and Heidi Yu, respectively, with permission.

Limitations

As a land-based technique that requires a stable platform, data collection occurs from a fixed position. Theodolite tracking is possible if animals reliably occur in a nearshore area (e.g., seasonal foraging grounds). However, many species have large ranges that are difficult to monitor from a single location. Researchers interested in tracking longer range movements along a shoreline have used multiple contiguous tracking sites with overlapping fields of view such that a moving focal individual can be "transferred" from one site to the next. For example, Gailey et al. (2016) used multiple theodolite teams in one of the most complex mitigation and monitoring plans developed for marine mammals, which required real-time tracking of western gray whales along approximately 20 km of coastline. This approach is limited if animals move too far offshore. Sighting bias may also result when documenting social behavioral states from an elevated fixed position. Although behavior can be observed with a theodolite, subtle behaviors that are difficult to see from a distance may be missed (e.g., intromission and/or conspecifics rubbing pectoral flippers); for these behaviors, boats, circling aircraft, or UAVs may be more appropriate. Theodolite studies tend to be limited in their ability to identify individuals or address individual heterogeneity in movement patterns based on factors such as sex, age, and reproductive status. Concurrent data collection by other methods (e.g., boat-based photo-identification or drone video recording) can complement theodolite tracking by contributing information on reliably recognizable individuals that may not be distinguished from shore (e.g., Best et al., 1995; Barendse et al., 2010).

Information Gathering

For a better understanding of how the theodolite has contributed to marine mammal science, a literature search was conducted and a Web-based survey was distributed through the MARMAM (Marine Mammals Research and Conservation Discussion) list-service, which has a wide membership of marine mammal researchers, students, and resource managers. The following information relating to marine mammal theodolite tracking was extracted from the literature and requested on the survey (see Supplemental Appendix 1 for full survey questions): location (i.e., country and state/province/region/prefecture) where theodolite tracking was conducted, species focus, data distribution outlets, and concurrent research methods (Supplemental Appendices 1 and 2 are available on the *Aquatic Mammals* website: https://www.aquaticmammalsjournal.org/index.php?option=com_content&view=article&id=10&Itemid=147). Although the goal of the literature search and survey was to collect as much information as possible, it is unlikely that all records of theodolite use in marine mammal research were obtained. One-hundred and fourteen papers were identified and reviewed, and 97 anonymous respondents participated in the survey. Results from the literature review and survey responses are presented in the following four sections.

Worldwide Distribution
Since the early 1970s, projects using theodolites to study marine mammals continue to develop around the globe. Based on combined data from the literature search and survey, theodolite tracking of marine mammals has been conducted on six continents in 36 countries (Figure 2).

Marine Mammal Species
There is a diversity of species tracked by theodolite, from blue whales (*Balaenoptera musculus*) to sea otters (*Enhydra lutris*). Based on our literature search and survey, 46 species of marine mammals (i.e., cetaceans, pinnipeds, sirenians, and mustelids) from 14 families have been tracked by theodolite (Table 1).

Data Distribution
Based on survey responses, results from marine mammal theodolite tracking research were disseminated via primarily peer-review journals, graduate-level theses, conference proceedings, and government/industry reports (Figure 3). Dissemination also included book chapters, popular articles, and websites which reach a broader audience than academia and government alone. Marine mammal theodolite tracking is accessible to diverse groups, in part because of the low cost involved and the lack of permits required to study marine mammals from shore. After initial equipment purchase, the only routine costs are small, typically less than $150 USD, and are associated with annual or semi-annual professional calibration and cleaning of the theodolite. In many cases, equipment can be borrowed or rented at a lower cost than if purchased.

Multi-Method Approach
Based on our survey and literature search, 69 and 60%, respectively, of projects involved multiple overlapping research platforms to study marine mammals. For both search methods, acoustic and boat-based approaches were most commonly incorporated with theodolite tracking (Figure 4). A number of research approaches may be integrated to fully investigate questions of interest—for example, passive acoustic recordings complement theodolite

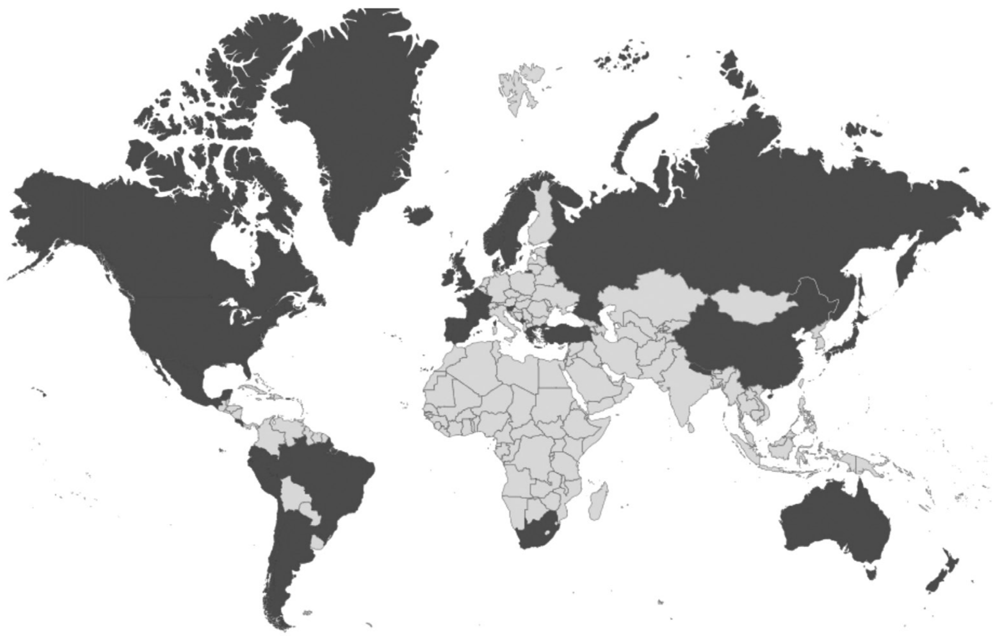

Figure 2. World map highlighting countries (dark gray shading) where marine mammals have been tracked by theodolite based on literature search and survey. Mapping source: https://www.amcharts.com/visited_countries/#

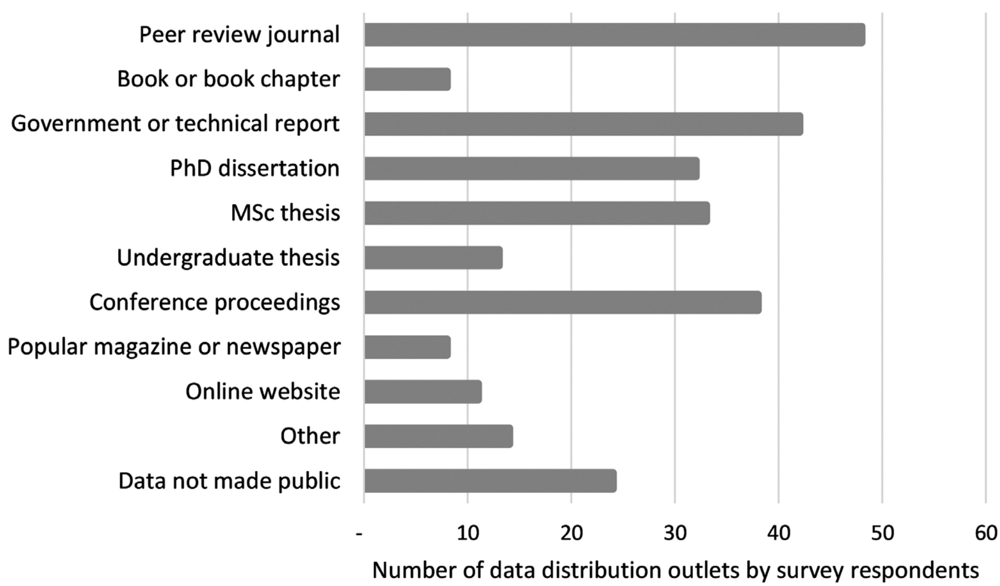

Figure 3. Outlets for research involving theodolite tracking of marine mammals based on survey results

tracking by recording vocalizations of dolphins in conjunction with behavioral observations that can shed light on vocalization context. With appropriate spatial sampling, this overlap of methods may also be used to estimate a detection function, enabling data to be translated into a local population density

Table 1. List of marine mammal species that have been tracked by theodolite. "a" indicates data obtained from the literature search; "b" indicates data collected from the survey. See Supplemental Appendix 2 for associated references.

Family	Genus species*	Common name	Reference source
Otariidae	*Eumetopias jubatus*	Steller sea lion	b
Phocidae	*Halichoerus grypus*	Grey seal	a, b
	Phoca vitulina	Harbor seal	a, b
Mustelidae	*Enhydra lutris*	Sea otter	b
Balaenidae	*Eubalaena glacialis*	North Atlantic right whale	b
	Eubalaena australis	Southern right whale	a, b
	Balaena mysticetus	Bowhead whale	a, b
Eschrichtiidae	*Eschrichtius robustus*	Gray whale	a, b
Balaenopteridae	*Megaptera novaeangliae*	Humpback whale	a, b
	Balaenoptera acutorostrata	Minke whale	a, b
	Balaenoptera edeni	Bryde's whale	b
	Balaenoptera physalus	Fin whale	a, b
	Balaenoptera musculus	Blue whale	b
Physeteridae	*Physeter macrocephalus*	Sperm whale	a, b
Ziphiidae	*Mesoplodon densirostris*	Blainville's beaked whale	b
Platanistidae	*Platanista gangetica*	South Asian river dolphin	a
Iniidae	*Inia geoffrensis*	Amazon river dolphin	b
Monodontidae	*Delphinapterus leucas*	Beluga whale	a, b
Delphinidae	*Cephalorhynchus eutropia*	Chilean dolphin	a, b
	Cephalorhynchus hectori	Hector's dolphin	a, b
	Steno bredanensis	Rough-toothed dolphin	b
	Sousa chinensis	Indo-Pacific humpback dolphin	a, b
	Sousa plumbea	Indian Ocean humpback dolphin	b
	Sotalia guianensis	Guiana dolphin	b
	Tursiops truncatus	Common bottlenose dolphin	a, b
	Tursiops aduncus	Indo-Pacific bottlenose dolphin	a, b
	Stenella attenuata	Pantropical spotted dolphin	b
	Stenella frontalis	Atlantic spotted dolphin	b
	Stenella longirostris	Spinner dolphin	a, b
	Stenella coeruleoalba	Striped dolphin	b
	Delphinus delphis	Common dolphin	a, b
	Lagenorhynchus acutus	Atlantic white-sided dolphin	b
	Lagenorhynchus obliquidens	Pacific white-sided dolphin	a, b
	Lagenorhynchus obscurus	Dusky dolphin	a, b
	Lagenorhynchus australis	Peale's dolphin	b
	Grampus griseus	Risso's dolphin	a, b
	Peponocephala electra	Melon-headed whale	b
	Pseudorca crassidens	False killer whale	a
	Orcinus orca	Killer whale	a, b
	Globicephala macrorhynchus	Short-finned pilot whale	b
Phocoenidae	*Neophocaena phocaenoides*	Indo-Pacific finless porpoise	b
	Phocoena phocoena	Harbor porpoise	a, b
	Phocoena spinipinnis	Burmeister's porpoise	b
	Phocoenoides dalli	Dall's porpoise	a, b
Trichechidae	*Trichechus inunguis*	Amazon manatee	a

*There is one report obtained by survey of tracking a basking shark (*Cetorhinus maximus*) with a theodolite, showing potential for this method with aquatic taxa outside of mammals.

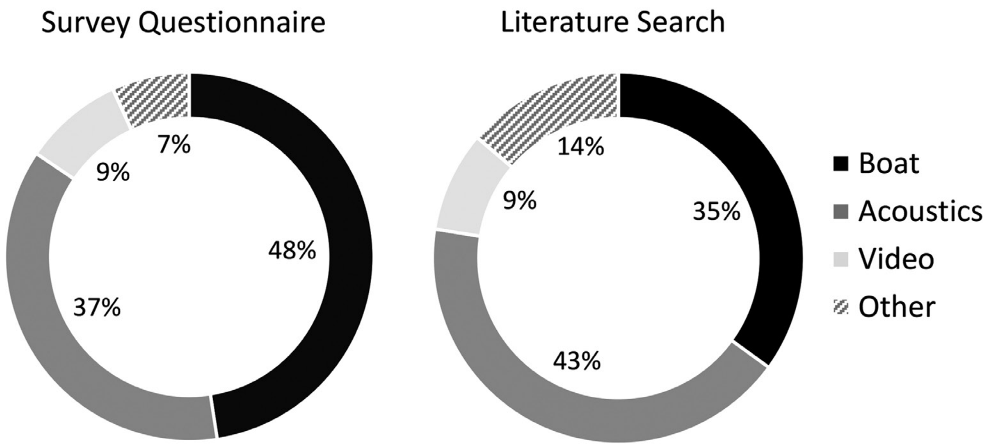

Figure 4. Research methods used simultaneously with theodolite tracking of marine mammals based on survey responses (*left*) and the literature search (*right*). The "Other" category refers to methods such as telemetry, carcass evaluation, biopsy, and aerial-based methods.

estimate of animals. Passive acoustic data collection can also extend observation periods beyond when visual observations are not possible, including during inclement weather and at night, to evaluate presence (see Munger et al., 2018, this issue). Gailey et al. (2016) used both real-time theodolite tracking of individual western gray whales and sound exposure estimates from seismic survey activity. Theodolite tracking determined whale position relative to mitigation boundaries that were established based on acoustic output from the seismic source. If whale positions overlapped with the mitigation boundary, seismic activity would cease in an attempt to minimize behavioral disturbance to individuals of this critically endangered population. Concurrent methods can complement theodolite tracking by contributing information that may not be possible to obtain from shore-based research alone.

Conclusions

Since the theodolite was first used to study marine mammals in 1972, it has been used in at least 36 countries to track at least 46 marine mammal species. The theodolite remains one of the most non-invasive and accurate ways to track free-ranging individuals and groups of marine mammals; it is useful for obtaining fine-scale movement patterns and broad-scale behavioral data to answer a range of ecological questions. The low cost associated with theodolite tracking enables researchers in diverse locations the opportunity to collect data with otherwise limited access to expensive research platforms. Theodolite tracking can be complemented with additional methods, such as passive acoustic monitoring and boat-based photo-identification, which compensate for limitations inherent in theodolite tracking. Potential sources of disturbance (e.g., boat-based tourism and construction activity) can be collected simultaneously with marine mammal data (Bejder & Samuels, 2003) in localized areas where the study of anthropogenic effects or real-time mitigation and monitoring is warranted. The theodolite has proven to be, and continues to be, a useful and lasting tool in marine mammal research, used globally to contribute to non-invasive marine mammal research, conservation, and management.

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