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INCREASING THE PRECISION OF THEODOLITE TRACKING: MODIFIED TECHNIQUE TO CALCULATE THE ALTITUDE OF LAND-BASED OBSERVATION SITES

H. Bailey
D. Lusseau
University of Aberdeen, School of Biological Sciences, Lighthouse Field Station,
Cromarty, Ross-shire IV11 8YJ, Scotland
E-mail: h.bailey@abdn.ac.uk

Knowledge of the location and speed of cetaceans is necessary to address a wide range of ecological and behavioral questions. Estimating the locations of cetaceans at sea can be extremely challenging, particularly where there are few notable landmarks or buoys to use as reference points. This has led to the increasing use of a surveyor's theodolite to track animals from land in a non-invasive manner (*e.g.*, Acevedo 1991, Harzen 1998, Bejder *et al.* 1999, Williams *et al.* 2002). A theodolite provides both the horizontal and vertical angle to a target. The vertical angle is given relative to gravity and the horizontal angle relative to a selected reference point of known position. These angles, together with the altitude of the theodolite and the position of the horizontal reference point, can be used to calculate the position of the target in (x,y) coordinates. The accuracy of these coordinates will depend on the accuracy inherent to the theodolite and that to which the altitude of the theodolite is known.

In some situations the altitude of the theodolite can be calculated using a surveying landmark of known altitude and location. However in remote field sites, such landmarks are often unavailable. Würsig *et al.* (1991) overcame this by providing a technique to calculate the altitude of the land-based observation site in the absence of such surveying landmarks (Fig. 1). This technique involves locating two points near the waterline with the same vertical angles (and thus equal distance from the theodolite). The distance between the theodolite and the mid-point between the two waterline sites can then be determined and consequently the altitude of the theodolite using trigonometry. However, practicalities in the field often make it difficult to position the points at equal distance from the theodolite and to place them near the waterline. This may be because of the rugged nature of the shoreline terrain or the orientation of the beach. It is also possible, especially on rocky shores, that two points of different height have the same vertical angle, but be unequal distances from the theodolite. Errors in these measurements will consequently reduce the precision with which the height of the theodolite is known. Lack of precision in the estimates of theodolite altitude will inherently lead to increased errors in the estimated location and hence distance travelled and speed of the target.

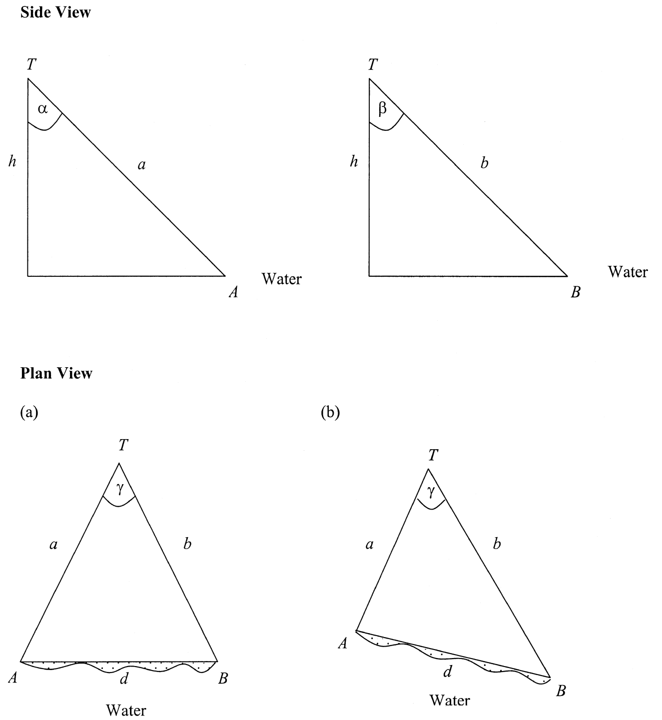


Figure 1. Schematic for determining theodolite altitude where *T* is the position of the theodolite. Using (a) the conventional method, lengths TA and TB would be equal, therefore angle $\alpha = \beta$. In (b) TA and TB are not equal lengths and consequently angles α and β are not equal.

We modified the computation technique described in Würsig *et al.* (1991) to permit calculation of the altitude of a land site without the assumption that the two points on the shore were at equal distance from the theodolite. Using this technique, measurements are logistically easier to obtain and less prone to errors, and should provide significantly more precise estimates of the theodolite altitude.

A theodolite (Leica T460) was positioned on a hill overlooking the entrance to the Inverness Firth (57°35′N, 4°06′W), a 1.3-km wide channel in northeast Scotland, that is used regularly by bottlenose dolphins (Wilson *et al.* 1997). Two points were positioned at the base of the cliff below the theodolite site at a known tidal height (low tide). This involved placing two people as close to the waterline as possible holding a 50-m long tape measure between them. Horizontal and vertical angle readings were taken of both ends of the tape measure using the theodolite. One person then remained in position near the waterline while the other moved along the beach so that the two points had the same vertical angle (and thus the same distance from the theodolite) while maintaining 50 m between them. The horizontal and vertical angles for both ends of the tape measure were again recorded. The two people then moved to another location along the shore. This was repeated at eleven locations and was performed during a sea state of Beaufort 1.

It was not possible to have two points at equal distance from the theodolite with 50 m between them at all locations along the shore as a result of the orientation of the beach. In cases where the two points had the same vertical angle, the height could be calculated using the technique described by Würsig *et al.* (1991). However, in every case in our study, it was not possible to position both points on the waterline using this technique as the orientation of the beach was not square to the theodolite. When the two points were positioned at the waterline using our modified technique, they were not at equal distances from the theodolite. This resulted in a scalene plan view triangle rather than an isosceles triangle and violated the assumption that right-angled trigonometry could be used in the calculations. The cosine rule (Fanchi 1997) was therefore applied instead to calculate the altitude of the theodolite by:

$$d^2 = a^2 + b^2 - 2ab\cos\gamma$$

$$a = \frac{h}{\cos\alpha} \qquad b = \frac{h}{\cos\beta}$$

$$d^2 = \left(\frac{h}{\cos\alpha}\right)^2 + \left(\frac{h}{\cos\beta}\right)^2 - 2\left(\frac{h}{\cos\alpha}\right)\left(\frac{h}{\cos\beta}\right)\cos\gamma$$

$$d^2 = \frac{h^2}{\cos^2\alpha} + \frac{h^2}{\cos^2\beta} - \frac{2h^2\cos\gamma}{\cos\alpha\cos\beta}$$

$$d^2 = h^2\left(\frac{1}{\cos^2\alpha} + \frac{1}{\cos^2\beta} - \frac{2\cos\gamma}{\cos\alpha\cos\beta}\right)$$

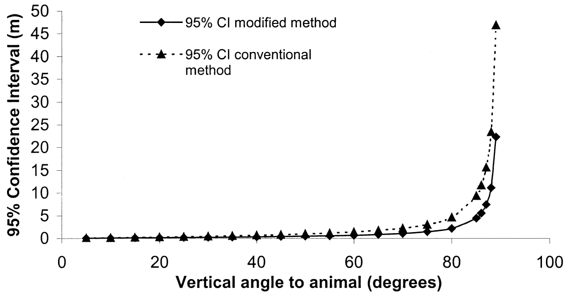
$$h = \sqrt{\frac{d^2}{\left(\frac{1}{\cos^2\alpha}\right) + \left(\frac{1}{\cos^2\beta}\right) - \left(\frac{2\cos\gamma}{\cos\alpha\cos\beta}\right)}}$$

$$h = \frac{d}{\sqrt{\left(\frac{1}{\cos^2\alpha}\right) + \left(\frac{1}{\cos^2\beta}\right) - \left(\frac{2\cos\gamma}{\cos\alpha\cos\beta}\right)}}$$

where h is the height of the theodolite, d is the distance between the two points at the waterline, a and b are the distances between the theodolite and the points at the waterline, α and β are the vertical angles, and γ is the horizontal angle between the two points (Fig. 1).

The mean altitude of the theodolite was calculated as 86.72 ± 0.693 (SD) m ($n = 11$) using the conventional method by Würsig *et al.* (1991) and 86.76 ± 0.330 m ($n = 11$) using our modified technique. Although these two heights are similar, the variation in the height estimation for the two methods was significantly different (Levene statistic = 5.262, $P = 0.033$). Our modified technique resulted in significantly less variation in the estimation of the altitude of the theodolite thus resulting in an increase in the precision to which the altitude of the theodolite is known. Consequently, the precision of the estimated position of the animal(s), distance travelled, and speed is improved. This improvement is most pronounced at larger distances from the theodolite, as the magnitude of distance errors is directly

(a)



(b)

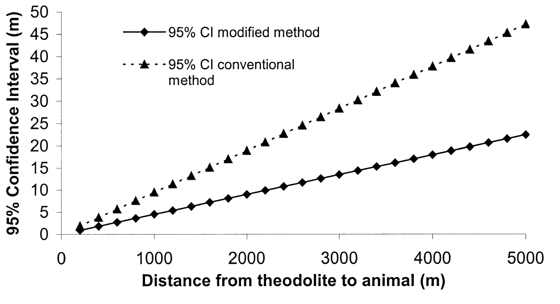


Figure 2. (a) Confidence interval around distance derived from the theodolite vertical angle reading (where zero is straight down) using the two altitude calculation methods. (b) Confidence interval at increasing distances from the theodolite given our theodolite height of 86.76 m.

proportional to the distance to a target. The 95% confidence interval around the estimated position begins to rise dramatically above a vertical angle of 70° (where 0° is straight down) for the conventional method, but not until 80° using the modified technique (Fig. 2a). At our theodolite height of 86.76 m, the error in distance estimation for an animal 1 km away is 4.5 m using the modified technique, whereas it is more than twice that using the conventional technique at 9.5 m (Fig. 2b). The error in the calculated position of a target at this distance is therefore considerably reduced using the modified technique. The reduction in error would be even more pronounced for theodolite sites at altitudes lower than the one used in this study, as the percentage error in the distance to an animal(s) is roughly proportional to the percentage error in the theodolite height measurement (Würsig *et al.* 1991).

The improved precision as a result of the modified technique will be of particular use in studies where positional errors are large in comparison to the distances measured. For example, investigating the speed of animals based on successive locations, distances between individual animals and animal groups, and distances to objects such as boats or fish farms. At 1 km away, the minimum distance between two objects for a gap between them to be detected is reduced from 19 m with the conventional method to 9 m with the modified technique. A bottlenose dolphin that moved 12 m (four body lengths) between theodolite readings would therefore appear to be stationary using the conventional method, whereas this movement would be detected with the modified technique.

Increases in positional precision are also especially important for studies that involve surveying animals over large areas, as positional errors increase with distance from the theodolite. Importantly, a much larger survey area can be examined for a given distance error using our modified technique as a result of the increase in positional precision. For example, for a given maximum distance error of 10 m using a theodolite at 86.76 m height, the study area can be more than double the size using our modified technique to calculate the altitude of the theodolite in contrast to the conventional method. This enables information to be gathered on animals that do not come as close to the shore, and for more extensive periods of time, as they are likely to be within the study area longer.

Although this modified technique will improve the estimation of the altitude of the theodolite, it is important that the tidal height is known at the time of each position as this will affect the height of the theodolite above sea level (Würsig *et al.* 1991). Errors may arise by not taking swell into consideration, and it could be advantageous to only record in constant weather conditions (Beaufort <3 for example).

The modified technique required measurements that were easier to obtain precisely and resulted in calculated heights that had significantly less variation than the conventional technique. The resulting increase in precision should reduce positional errors, enabling larger survey areas to be studied and increasing the number of potential theodolite sites as lower altitudes may be used. This technique should therefore make a valuable contribution to increasing the precision of recording animal movements and assessing interactions with other species and human activities.

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Literature Cited

Acevedo, A. 1991. Behaviour and movements of bottlenose dolphins, *Tursiops truncatus*, in the entrance to Ensenada De La Paz, Mexico. Aquatic Mammals 17:137–147.

Bejder, L., S. M. Dawson and J. A. Harraway. 1999. Responses by Hector's dolphins to boats and swimmers in Porpoise Bay, New Zealand. Marine Mammal Science 15:738–750.

Fanchi, J. R. 1997. Math refresher for scientists and engineers. John Wiley and Sons, New York, NY.

HARZEN, S. 1998. Habitat use by the bottlenose dolphin (*Tursiops truncatus*) in the Sado Estuary, Portugal. Aquatic Mammals 24:117–128.

WILLIAMS, R., A. W. TRITES AND D. E. BAIN. 2002. Behavioural responses of killer whales (*Orcinus orca*) to whale-watching boats: Opportunistic observations and experimental approaches. Journal of Zoology 256:255–270.

WILSON, B., P. M. THOMPSON AND P. S. HAMMOND. 1997. Habitat use by bottlenose dolphins: Seasonal distribution and stratified movement patterns in the Moray Firth, Scotland. Journal of Applied Ecology 34:1365–1374.

WÜRSIG, B., F. CIPRIANO AND M. WÜRSIG. 1991. Dolphin movement patterns: Information from radio and theodolite tracking studies. Pages 79–111 *in* K. Pryor and K. S. Norris, eds. Dolphin societies. University of California Press, Berkeley, CA.

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